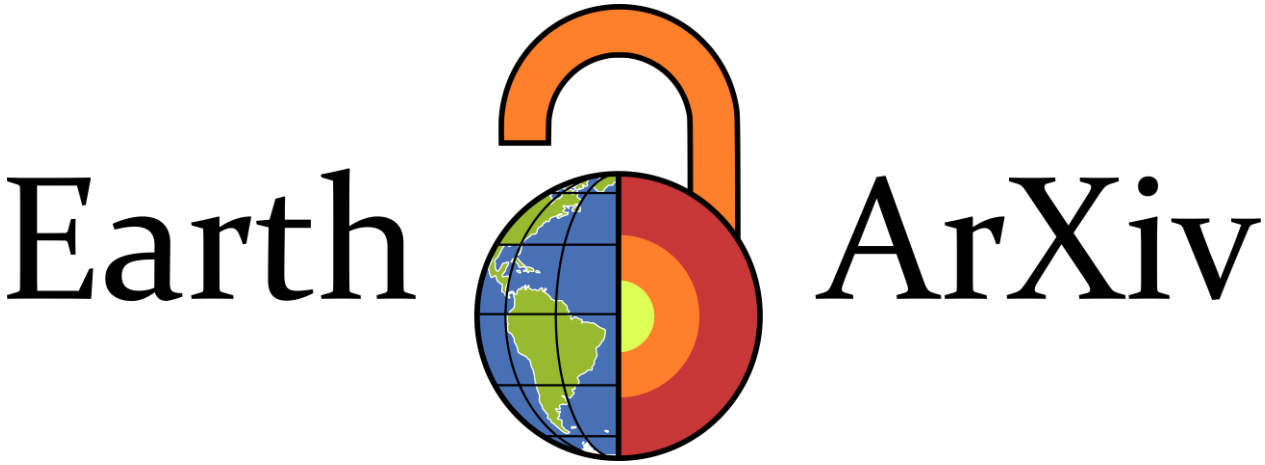


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Polymineralic synneusis in silicic magmas: Evidence from the microstructures and orientation relationships of inclusions in K-feldspar megacrysts

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ABSTRACT

Crystal aggregation via synneusis is well-documented in many common igneous minerals, such as quartz and olivine. Synneusis is typically described as a monomineralic process whereby two crystals of the same mineral adhere in specific low-energy orientation relationships. In contrast, unlike minerals are generally assumed to be antipathetic. Nonetheless, the occurrence of polymineralic synneusis (systematically oriented attachment of unlike mineral pairs) has been postulated but never quantitatively demonstrated. Therefore, the occurrence and characteristics of polymineralic synneusis, and its impacts on the behaviour of magmatic systems, remain poorly understood.

We apply spatially correlated microstructural analyses, including electron backscatter diffraction and cathodoluminescence mapping, to test whether polymineralic crystal aggregates can form via synneusis. The abundant mineral inclusions within K-feldspar megacrysts in granites have previously been postulated to arise from polymineralic synneusis, therefore we chose to study examples of this texture from two unrelated plutons. Textural

observations confirm that inclusions of plagioclase, amphibole and various accessory minerals grew independently in the magma before attaching to the megacrysts.

Analysis of the crystallographic orientations of plagioclase, amphibole, titanite and magnetite relative to their host K-feldspar reveal variably systematic orientation relationships. Plagioclase, amphibole and titanite show distinct suites of orientations within each growth sector of the K-feldspar, while magnetite does not. Titanite orientations appear to be controlled mainly by shape, whereas amphibole orientations cannot easily be explained by shape alone, so may also have a crystallographic control. Plagioclase orientations are tightly crystallographically controlled due to the lattice similarities between K-feldspar and plagioclase. Some of the observed K-feldspar-plagioclase orientation relationships follow established feldspar twin laws, which represent low-energy grain interfaces. However, we also observe orientation relationships that have not been documented as growth twins and are diagnostic synneusis relationships. In particular, the predominance of combined Baveno-type relationships resulting from the attachment of (010) and (001) feldspar faces appears to be unique to synneusis. We infer that crystals encountering each other in the magma attached, and then rotated into more favourable orientations, due to the minimisation of interfacial energy.

Synneusis has been considered diagnostic of low-viscosity, low-crystallinity magmas, but our results demonstrate that this is not always the case, as the megacrysts grew in relatively viscous, silicic, crystal-rich magma. The occurrence of polymineralic synneusis even in these granitic systems suggests that it may be an important and widespread magmatic process, creating crystal clusters that potentially impact both the rheological behaviour and geochemical evolution of the host magma.

Keywords: (up to 5, alphabetical, separated by semicolons)

EBSD; Granite; Megacryst; Microstructure; Synneusis

INTRODUCTION

Crystal clusters are ubiquitous in igneous rocks and can be valuable archives of information about magmatic processes. Interpreting the petrological significance of crystal clusters hinges on understanding the mechanisms by which they form. A variety of cluster-forming mechanisms may operate in magma, each with distinct petrogenetic implications. Clusters and similar microstructures have been attributed to processes including heterogeneous nucleation (Kirkpatrick, 1977; Hammer *et al.*, 2010), mush disaggregation (Cashman *et al.*, 2017; Neave *et al.*, 2017), growth twinning (Dowty, 1980), resorption (Hogan, 1993), disequilibrium crystallisation (Barbee *et al.*, 2020; McCarthy *et al.*, 2020), dendrite annealing (Welsch *et al.*, 2013), and synneusis (e.g., Vance, 1969).

Synneusis is the attachment of crystals that originally grew independently in melt before converging and joining (Vogt, 1921). Vogt (1921) introduced the term with reference to monomineralic clustering, but in an influential later paper, Vance (1969) broadened the definition to include polymineralic synneusis. Vance also added the important observation that synneusis typically occurs via attachment on important crystallographic planes, and in preferred orientations defined by positions of low interfacial energy (Vance, 1969). Although some authors have since mentioned synneusis in a polymineralic context (e.g., Vernon, 2018), research on the process of synneusis, and its petrological implications, has focused on monomineralic synneusis. Detailed microstructural work has revealed evidence of monomineralic synneusis in a variety of common igneous minerals, including olivine (Schwindinger and Anderson, 1989; Wieser *et al.*, 2019), plagioclase (Vance, 1969; Bennett *et al.*, 2019), chromite (Holness *et al.*, 2023), zircon (Jocelyn and Pidgeon, 1974;

72 Alexandrov, 2001) and quartz (Beane and Wiebe, 2012; Dyck and Holness, 2022; Dyck,
73 2023).

74 In recent years, studies of synneusis have greatly benefitted from the application of
75 crystallographic orientation mapping by electron backscatter diffraction (EBSD). EBSD
76 enables quantification of crystallographic orientation relationships (CORs) between adjacent
77 crystals (Habler and Griffiths, 2017), confirming that synneusis attachments preferentially
78 occur on significant crystallographic faces and feature characteristic CORs (e.g., Beane and
79 Wiebe, 2012). Monomineralic synneusis clusters are characterised by coincident-site lattice
80 relationships where the lattices of neighbouring grains are aligned to minimise the energy of
81 the grain boundary, e.g., twin laws (Dyck and Holness, 2022; Dyck, 2023).

82 EBSD also introduces the potential to quantify CORs between unlike crystal pairs.
83 Such analysis has already been applied to magmatic epitaxial relationships (Hammer *et al.*,
84 2010), xenocryst reaction rims (Schuster *et al.*, 2023) and inclusions in garnet (Griffiths *et*
85 *al.*, 2016). Furthermore, recent EBSD analysis indicated that highly systematic CORs can
86 result from the synneusis of K-feldspar and plagioclase in granite (Gordon and Wallis, 2024)
87 but the sample size in that study was insufficient to allow thorough characterisation of the
88 CORs present. Low-energy relationships in monomineralic systems are relatively
89 straightforward to model with reference to common faces, twin laws, and coincident-site
90 lattice modelling (Dyck and Holness, 2022), whereas polymineralic orientation relationships
91 are more challenging to characterise and benefit from the analysis of large datasets (Griffiths
92 *et al.*, 2016). EBSD therefore presents a gateway to studying the phenomenon of
93 polymineralic synneusis.

94 At present, we know very little about whether unlike mineral pairs are “sticky” towards
95 each other in magmas, and the default assumption is that they are antipathetic: that if two
96 crystals of different minerals were to encounter each other in magma, there would be no

significant drive for them to adhere. However, polymineralic synneusis is challenging to distinguish from other clustering mechanisms using standard petrographic or geochemical methods, and therefore its prevalence may have been underestimated. To assess the occurrence and significance of polymineralic synneusis, a new approach is necessary. Systematic orientation relationships between unlike pairs of minerals may prove diagnostic of synneusis, even in otherwise cryptic clusters.

To develop polymineralic synneusis as a useful petrological tool, we must first define its characteristic orientation relationships and textures. We must also consider the magmatic conditions under which polymineralic synneusis occurs, so that when evidence of polymineralic synneusis is identified in the rock record, meaningful petrogenetic inferences can be made. In this paper, we aim to undertake foundational work towards these goals.

Megacrysts: ideal for characterisation of polymineralic synneusis

Oriented inclusions in K-feldspar megacrysts in granites are the quintessential microstructure thought to arise from polymineralic synneusis. Euhedral, systematically arranged inclusions of plagioclase, amphibole, biotite and other minerals are ubiquitous in alkali feldspar megacrysts (e.g., Booth, 1968; Cox *et al.*, 1996; Vernon and Paterson, 2008), and are frequently ascribed to synneusis (e.g., Hibbard, 1965; Vernon, 1986; Moore and Sisson, 2008; Gordon and Wallis, 2024). Vance (1969) commented that “K-feldspar phenocrysts with oriented plagioclase inclusions are among the most spectacular and useful of the common synneusis structures”.

Megacryst inclusions also make an excellent case study because each megacryst typically contains thousands of small inclusions of a variety of minerals. Abundant small inclusions in one large host crystal are ideal for COR identification (Griffiths *et al.*, 2016),

and the presence of inclusions of a range of common rock-forming minerals enables a variety of mineral-pair CORs to be characterised and compared.

The petrological significance of synneusis in granites

Synneusis is commonly thought to be confined to low-viscosity melts, in which crystals can easily move relative to each other via settling (Schwindinger and Anderson, 1989; Schwindinger, 1999; Alexandrov, 2001; Wieser *et al.*, 2019), turbulent flow (Vance, 1969) and bidirectional conduit flow (DiBenedetto *et al.*, 2020). Granites therefore seem an unlikely environment for synneusis, because even at low crystallinities they have viscosities high enough to impede turbulent flow and crystal settling (Glazner, 2014). However, synneusis in granites appears to be widespread (e.g., Beane and Wiebe, 2012; Dyck and Holness, 2022) and is not even confined to low crystallinities; Gordon and Wallis (2024) found that the synneusis of plagioclase and K-feldspar megacrysts occurs at moderate crystallinities of ~35–55% crystals.

The occurrence of synneusis in these high-viscosity, crystal-rich systems raises fundamental questions about the processes by which crystals interact and adhere to each other in magmas. Synneusis microstructures may not be reliable indicators of low crystallinity environments, or of commonly invoked processes such as settling. Therefore, the latter part of this paper discusses some possible mechanisms by which crystals may come together in silicic melts and attach in systematic orientations.

GEOLOGICAL BACKGROUND

K-feldspar megacrysts containing oriented inclusions are extremely common in silicic plutons. We chose to sample two unrelated calc-alkaline batholiths: the well-studied Tuolumne Intrusive Complex in California, and the Separation Point Granite in New Zealand.

146 The Tuolumne Intrusive Complex, in the Sierra Nevada batholith, comprises older
147 (from ~95 Ma), more mafic granodiorites and tonalites around the margins, and progressively
148 younger (to ~85 Ma) and more evolved granodiorite and granite units toward the centre
149 (Bateman and Chappell, 1979; Coleman *et al.*, 2004). We sampled the two main megacrystic
150 units of the complex: the central Cathedral Peak Granodiorite (CP) and the slightly less
151 evolved Porphyritic Half Dome Granodiorite (pHD).
152 The Separation Point Batholith (SP) is situated in the north of New Zealand's South
153 Island, and is approximately 120 km long and around 10 km wide. The batholith is mainly
154 composed of homogeneous, medium- to coarse-grained, biotite-hornblende monzogranite,
155 but also includes granodiorites (Muir *et al.*, 1995). The north of the batholith is zoned from
156 equigranular hornblende-biotite monzogranite in the west to K-feldspar megacrystic biotite
157 monzogranite in the east (Muir *et al.*, 1995), and we sampled the latter. U/Pb geochronology
158 of zircons from the Separation Point Granite yields a pooled age of 112±1.9 Ma (Bolhar *et*
159 *al.*, 2008).
160 The field characteristics of the two plutons are similar. Megacrysts are distributed
161 heterogeneously, with local concentrations interpreted as areas of physical accumulation (e.g.,
162 Vernon, 1986; Vernon and Paterson, 2008). The megacrysts are commonly aligned in a
163 magmatic fabric (Fig. 1) both in the normal bulk granite, and in outcrop-scale structures such
164 as ladder dykes and enclave swarms. Megacrysts are sometimes aligned such that their main
165 faces are flat against their neighbours' faces, but they do not impinge on one another except
166 in their anhedral overgrowth rims (Fig. 1b).
167

METHODS

Sampling and sample preparation

Field observations were made in both study areas to establish petrological context and ensure that the samples collected were representative. We sampled ten sites across the Tuolumne Intrusive Complex, and made thin sections of two megacrysts and one groundmass sample per site. Where possible, the megacrysts were cut through their cores and normal to a major face. Four representative megacrysts for large-area EBSD mapping (Fig. 2), were selected based on freshness, abundance of inclusions, and simplicity of megacryst morphologies. One of the megacrysts included in this study (Sample G) was previously described by Gordon and Wallis (2024). Sampling locations are given in Table 1.

At the Separation Point Batholith, weathered-out euhedral megacrysts are abundant in local drift deposits and we collected loose megacrysts from beaches near Kaiteriteri. Sampling loose megacrysts enabled us to identify the exterior faces of the megacrysts and cut sections through the cores. Two megacrysts were sectioned, and one was selected for large-area EBSD mapping.

Petrography and geochemistry

We examined thin sections of the megacrysts, their inclusions and the associated groundmass using transmitted light microscopy. QEMSCAN mapping was performed with a step size of 10 μm on a FEI Quanta 650 field emission gun scanning electron microscope (SEM) equipped with two energy-dispersive X-ray spectrometry (EDS) detectors. Cathodoluminescence (CL) mapping was conducted on the same SEM.

Electron backscatter diffraction

We conducted EBSD mapping of the Tuolumne megacrysts on a Zeiss Gemini 300 SEM with an Oxford Instruments Symmetry detector and Aztec 4.0 acquisition software. EBSD on the Separation Point sample was performed on a FEI Quanta 650 SEM with an Oxford Instruments Symmetry S3 detector and Aztec 6.1 acquisition software. We used apertures of 100–120 μm and accelerating voltages of 20–30 kV. Working distances were typically 23–25 mm, and patterns were collected using Speed 1 mode. The Tuolumne samples were mapped at high vacuum with a 6 nm carbon coat, and the SP sample was mapped uncoated at low vacuum. The maps have step sizes of 10–20 μm, which are small enough to capture most plagioclase inclusions. Misindexing between K-feldspar and plagioclase was minimised by using an anorthite match unit for plagioclase, as described by Gordon and Wallis (2024). K-feldspar was indexed using an orthoclase match unit. Titanite was indexed against a match unit derived from Hawthorne *et al.*, (1991), which uses a different unit cell setting to the conventional morphological setting. We therefore converted our titanite Miller indices to the morphological setting.

We performed initial de-noising in CHANNEL5 Tango software by removing wild spikes. For maps with poor indexing, we also created filled versions of the datasets to minimise loss of inclusions with a low number of indexed pixels during the manual screening procedure outlined below.

Comparison of the EBSD maps with CL and transmitted light images revealed that a substantial number of the indexed plagioclase grains were either exsolved albite, or systematic misindexing of K-feldspar. To alleviate this issue, all plagioclase grains in each EBSD dataset were manually screened with the aid of CL and transmitted light microscopy so that only genuine inclusions were accepted into the dataset for analysis. Where plagioclase inclusions contained multiple twins, only one of each twin orientation was included in the

dataset, to remove the bias towards large inclusions with polysynthetic twins. Only one twin was detected in most plagioclase grains, but this is most likely a sampling artifact, as polysynthetic twinning is visible in almost all plagioclase grains with cross-polarised transmitted light at high magnification. Therefore, the detected orientation of a given inclusion may not always represent the twin member that actually formed the attachment surface with the host crystal, but is likely related to it by a twin law, most commonly the albite or pericline law.

Further EBSD data processing was performed using MTEX version 5.10.2, an open-source toolbox for manipulating EBSD data (Bachmann *et al.*, 2010), in MATLAB R2020b. All inclusion orientations were rotated into a reference frame defined by the crystal lattice of the host megacryst (Fig. 7), enabling data from multiple megacrysts to be pooled. CL and EBSD data were used to identify the megacryst growth sector that each inclusion lay within; in other words, which face of the megacryst each inclusion interacted with during its incorporation (Fig. 2). The megacryst faces in each map were identified by comparing the zonation visible in CL to stereonet projections of the traces of possible faces modelled from the EBSD data. Data from faces that could not be identified were excluded.

Where the MTEX crystalShape function was used to visualise orientations, the crystalShape habits were customised to match as closely as possible the actual habits of each mineral in the samples.

PETROGRAPHIC AND GEOCHEMICAL RESULTS

Every megacryst studied contains abundant inclusions (Fig. 3), which are predominantly of plagioclase, although every mineral present in the groundmass except quartz also occurs as euhedral inclusions. Inclusions are concentrated in particular growth zones of the host crystal, and sometimes also in particular megacryst growth sectors. The

241 inclusions have shape preferred orientations parallel to the euhedral form of their host
242 megacryst. In the following sections we describe the Tuolumne megacrysts first, before
243 providing observations of the Separation Point megacrysts for comparison.
244
245 **Textures of the Tuolumne megacrysts**
246 Megacrysts feature euhedral cores 2–10 cm long, with overgrowth rims that extend
247 interstitially into the groundmass. The overgrowth rims are a subtly different colour in hand
248 specimen, and typically have finer-scale exsolution lamellae than the euhedral cores.
249 Microcline twins, where present, tend to be coarser near grain boundaries.
250 The megacrysts have complex concentric zones that are broadly euhedral, with planar
251 surfaces that can be assigned to the common growth faces of K-feldspar (Fig. 4b). Each zone
252 is CL-bright towards the interior of the crystal, gradually darkening towards the rim, before a
253 sharp transition back to CL-bright K-feldspar, and the repetition of the pattern. The sharp
254 zone boundaries can be near-planar, undulating or embayed, and sometimes truncate
255 boundaries that lie to the interior of the crystal. The gradient in CL brightness of each zone
256 follows the topography of its underlying boundary.
257 Inclusions have a variety of spatial relationships to the megacryst zones, and can occur
258 anywhere within a zone, although some zones host more inclusions than others. Euhedral
259 inclusions almost never occur flush against a smooth planar zone boundary in the megacryst.
260 Inclusions commonly sit in a shallow embayment in the zone boundary, where the
261 embayment follows the shape of the inclusion (Fig. 4a, c, d). Similar shallow embayments
262 with no visible inclusion may be associated with one lying outside the plane of view. Some
263 inclusions sit within a zone or, less commonly, across a zone boundary with no embayment.
264 Rarely, an inclusion sits on a segment of zone boundary that stands proud from the
265 surrounding boundary. Horizons containing many large euhedral inclusions are generally

associated with an underlying deeply incised boundary that truncates several previous zones (e.g., left hand edge of Fig. 4c).

CL also reveals the presence of complex embayments with irregular linear or branching shapes that have no relationship to the normal growth zones (e.g. Fig 4f). These deep embayments sometimes contain inclusions with atypical orientations. The embayments contain CL-dark K-feldspar, which is sometimes finely banded parallel to the embayment margins, with cross-cutting relationships indicating inwards growth. Some embayments are fracture-like in form with CL-uniform interiors, while those with complex fine bands tend to be smooth-edged and wider. There is never any visible offset across the embayments. The cores of the embayments are often quartz (Fig. 4f), which is usually unzoned but occasionally features contact-parallel zones. Neighbouring embayments sometimes contain seemingly separate cores of quartz that are in crystallographic continuity with each other and are most likely interconnected outside the plane of view. Similar quartz patches surrounded by CL-dark K-feldspar occur in association with some inclusions, especially filling the gaps between crystals in clusters (Fig. 3).

Plagioclase inclusions

The Tuolumne plagioclase inclusions are texturally diverse. Some are large (up to ~4 mm long) and euhedral, but there are also abundant smaller inclusions, many of which are anhedral. Zonation that is visible in cross-polarised light is more common in the larger inclusions. Inclusions commonly have a ragged rim of albite that is in optical continuity with neighbouring perthitic albite lamellae. EDS confirms that the zoned plagioclase inclusions have more calcic cores and more sodic rims, as well as irregular albite rims (Fig. 4e). Elongate euhedral inclusions usually have their long axes oriented approximately parallel to

the zones/face of the host. Where plagioclase inclusions occur in contact with each other, they often have parallel or twinned relationships with their neighbours.

Large, euhedral plagioclase inclusions are generally more common towards the outside of the megacryst, or sometimes in a distinct growth horizon within the megacryst, associated with a deeply incised zone boundary. Relatively planar zone boundaries are occasionally followed by abundant small anhedral plagioclase inclusions.

In CL, the plagioclase inclusions sometimes feature clear concentric euhedral zones, especially in the larger inclusions (Fig. 4d). The zonation patterns of large euhedral inclusions in the outer parts of the megacryst sometimes match those of the groundmass plagioclase. Some plagioclase inclusions, especially those that are small and anhedral, have fine-scale complex zones. Plagioclase inclusions within any given growth zone of a megacryst can have a wide variation in their own internal zonation patterns.

Quartz inclusions

Quartz inclusions are common in the Tuolumne megacrysts and can be up to approximately 3mm long. The inclusions are anhedral, usually blobby or elongate, and usually associated with the cores of complex embayments. Linear inclusions feature tapering protrusions into the surrounding K-feldspar. Seemingly separate but neighbouring quartz inclusions often enter extinction simultaneously. Euhedral inclusions of quartz are extremely rare and only occur at the margins of megacrysts.

Inclusions of other phases

All of the megacrysts contain accessory minerals, but mafic minerals are more abundant in the megacrysts of the less evolved pHD than they are in the CP megacrysts.

Amphibole inclusions are typically < 1.5 mm long and euhedral. Euhedral zones are sometimes visible in cross-polarised light, and simple twins are common (Fig. 5). Amphibole sometimes occurs in small clusters with parallel faces (Fig. 5) and often occurs alongside magnetite. Amphibole inclusions are commonly oriented with their long axes roughly parallel to the host face. While some amphiboles appear to have a face parallel to that of the K-feldspar host, others do not (Fig. 5).

Biotite is rarely included in the megacrysts despite being common in the groundmass. Where biotite inclusions occur, they tend to be clustered with other mafic minerals. Isolated biotite inclusions are typically oriented with their cleavage parallel to the trace of the face of the host, and are most abundant near the megacryst rims.

Various accessory minerals are present in the megacrysts. Titanite occurs as euhedral diamond or kite shaped crystals, usually < 1mm long, with complex concentric zones visible in BSE images. Titanite inclusions typically have a long axis or major face parallel to the trace of the host face. Equant, subhedral magnetite crystals occur both as solitary inclusions, and in clusters of mafic minerals. Apatite crystals are typically euhedral, and often occur in clusters with mafic inclusions.

K-feldspar inclusions in the K-feldspar megacrysts are extremely rare. CL occasionally hints at the presence of a K-feldspar inclusion with an orientation the same as that of its host, and one thin section contains an inclusion with an orientation different to that of its host, which will be discussed below.

Groundmass textures

The groundmass crystals are generally much larger than inclusions of the same phase, and this effect is especially pronounced for plagioclase. The groundmass plagioclase features

338 complex oscillatory zonation and often occurs in clusters of several plagioclase crystals that
339 appear to have systematic orientation relationships.
340 Quartz is an interstitial phase in the groundmass, although its internal zonation
341 sometimes records an early stage of euhedral growth. Sometimes the zones also contain
342 smoothed non-euhedral boundaries suggestive of resorption. No irregularly shaped dendritic
343 or embayed zone morphologies were observed.
344 The K-feldspar in the groundmass is unzoned, both in cross-polarised light and CL, and
345 is interstitial between groundmass crystals of plagioclase. Groundmass K-feldspar is often a
346 crystallographically continuous overgrowth of a nearby megacryst. Non-megacrystic
347 groundmass crystals do occur, but are indistinguishable from megacryst overgrowths in CL
348 images. In at least one case (Sample I), the orientation of the contact between the groundmass
349 K-feldspar originating as a megacryst overgrowth and the independent groundmass K-
350 feldspar is defined by the crystallography of the latter, with the groundmass crystal therefore
351 appearing to predate the megacryst overgrowth. In most other cases, the groundmass crystals
352 are anhedral and have irregular contacts with other K-feldspar groundmass crystals.
353 Exsolution lamellae are less well developed in the groundmass K-feldspar than in the
354 megacrysts.
355 The mafic and accessory minerals in the groundmass are euhedral to subhedral, and
356 larger than their counterparts included within the megacrysts. Mafic minerals typically occur
357 in clusters, and most apatite is included within biotite or amphibole, sometimes in apparently
358 systematic orientations.
359
360 **Petrography of the Separation Point megacrysts**
361 The SP samples are texturally similar to those from Tuolumne. The megacrysts are
362 perthitic, with coarser exsolution lamellae in their cores than their rims, and microcline twins

363 that coarsen near the albite lamellae. The inclusions are concentrically arranged and have a
364 strong shape preferred orientation parallel to the faces of the host megacryst. The inclusion
365 assemblage comprises mostly plagioclase, with rare euhedral titanite and equant iron oxides.
366 Altered polycrystalline biotite and chlorite occasionally appear to have pseudomorphed
367 amphibole. Albite rims on plagioclase inclusions are rarer in the SP megacrysts than those
368 from Tuolumne but are sometimes present. As with the Tuolumne megacrysts, the SP
369 megacrysts lack euhedral quartz inclusions but feature elongate slug-like quartz inclusions.
370 The groundmass comprises plagioclase, quartz, alkali feldspar and biotite, with
371 accessory iron oxides and apatite. Undulose extinction in the quartz and kinks in the biotite
372 record mild deformation.
373
374 **EBSD RESULTS**
375 This section describes the habits, faces and twins of the minerals of interest, then
376 presents the orientation distributions of the inclusions. Particular attention is given to
377 plagioclase, which has the most complex orientation relationships with the host.
378
379 **Crystal habits and twins**
380 The megacrysts from both batholiths have prominent (010) and (001) faces with
381 smaller {110} and ($\bar{2}$01) faces. Simple twins are common, but we chose to avoid them for the
382 EBSD maps, except in sample G which contains four twin members related by Baveno and
383 Manebach laws (Fig. 2).
384 The plagioclase crystals have habits with large (010) and (001) faces, and are
385 ubiquitously twinned, most commonly on the albite, Carlsbad, albite-Carlsbad, pericline, and
386 Ala laws. The amphibole crystals are elongate along [001], with prominent {110} faces and

smaller or absent (010) and (100) faces. The titanite crystals have prominent {111} faces and occasionally also show minor faces including (100) and (001).

3D axis-angle plotting to check for crystallographic orientation relationships

Plotting the host-inclusion data in axis-angle space allows a rapid qualitative assessment of whether any systematic CORs are present in the data, in a way that inherently accounts for the symmetry mismatch between different minerals (Fig. 6). We pooled the inclusion data from all of the EBSD datasets, and plotted the misorientations between the K-feldspar and the inclusion minerals following the methods of Krakow et al. (2017). Misorientations between crystals are plotted in a 3D vector space, where the magnitude of the vector (the distance from the origin) corresponds to the misorientation angle (ω), and the direction corresponds to the misorientation axis in a common reference frame where [001] of every mineral lies along z and (100)* lies along x. The shape of the 3D fundamental region required to plot the data is determined by symmetry, for which Krakow et al. (2017) provide details. We coloured each datum according to the megacryst growth sector in which the inclusion is located.

In the plots, tight clusters of points correspond to specific CORs. A radial line of points indicates that crystals are related by continuous rotation about a specific axis. Loose clusters indicate that the misorientations are non-random but contain scatter in both axis and angle of misorientation.

The plagioclase misorientations are highly organised, with at least 14 specific CORs (Fig. 6a, b). Even data outside these CORs are preferentially arrayed along particular radial lines (indicating preferred misorientation axes) and at particular distances from the origin (indicating preferred misorientation angles). Some CORs are only present within particular growth sectors of the host plagioclase.

412 Titanite and amphibole both display moderately organised misorientation data (Fig. 6c–
413 f). No strong specific CORs are present, but the misorientation data are not randomly
414 distributed. In both minerals, inclusions from each megacryst sector cluster loosely together.
415 Magnetite misorientations are poorly organised (Fig. 6g, h). The few linear
416 arrangements that appear in axis-angle space (e.g., projected over the origin in Fig. 6h)
417 comprise < 5 points, and a much larger dataset would be required to assess whether they are
418 significant, therefore we do not discuss them further.
419
420 **General statement on the plagioclase inclusion orientations**
421 EBSD reveals that the orientations of the plagioclase inclusions are strongly systematic
422 in every sample. The megacryst growth sectors associated with each major face contain
423 distinctive suites of associated plagioclase orientations (Fig. 8). Orientation systematics in
424 each megacryst sector were consistent across all samples from both batholiths. In the
425 following plots, we have therefore pooled data from all Tuolumne megacrysts into one set of
426 pole figures. Data from the SP sample, which had (010) and (001) growth sectors, are
427 presented separately for comparison.
428 As established by Gordon and Wallis (2024), crystals that lie in the groundmass beyond
429 the euhedrally zoned portion of the megacrysts have random orientations, even though many
430 of them are in contact with interstitial K-feldspar that is in crystallographic continuity with
431 the megacrysts. We found the same to be true in the samples of this study, therefore
432 inclusions situated beyond the euhedrally zoned portions of the megacrysts were excluded
433 from all further analysis.
434 In the remainder of this paper, Miller indices have a subscript with a mineral
435 abbreviation where there could be ambiguity about which mineral they concern, e.g., $(010)_{Kfs}$
436 refers to (010) planes of K-feldspar, while $(010)_{Pl}$ refers to (010) planes of plagioclase. Where

statements apply to both minerals, or the context is unambiguous, no subscript is used. All pole figures are plotted in the standard K-feldspar reference frame defined in Fig. 6. Pole figures are lower hemisphere unless otherwise specified.

Plagioclase inclusions in megacryst (010) growth sectors

The plagioclase inclusions hosted within $(010)_{Kfs}$ growth sectors have systematic orientations. In the $(010)^*_{Pl}$ pole figures (Fig. 9), the data cluster tightly around the location of $(010)^*_{Kfs}$, demonstrating that the (010) planes of the two minerals are often parallel. As [010] and (010)* are near-parallel in plagioclase, the distributions of $[010]_{Pl}$ and $(010)^*_{Pl}$ match closely, but the clustering of $(010)^*_{Pl}$ is slightly tighter.

$(001)^*_{Pl}$ data form three main clusters. One cluster is parallel to $(010)^*_{Kfs}$, and a pair of clusters are located where $(001)^*_{Pl}$ poles are situated ~25° to either side of $[001]_{Kfs}$ within the $(010)_{Kfs}$ plane. Most $[001]_{Pl}$ axes lie within the $(010)_{Kfs}$ plane, mainly clustered around $[001]_{Kfs}$ but also in two smaller clusters approximately 60° to either side. $[001]_{Pl}$ axes also occur within a small circle ~25° away from $(010)^*_{Kfs}$.

$[100]_{Pl}$ are almost all concentrated within the $(010)_{Kfs}$ plane, mostly in two major clusters ~65° to either side of $[001]_{Kfs}$, with a third cluster parallel to $[001]_{Kfs}$.

Plagioclase inclusions in megacryst (001) growth sectors

Plagioclase inclusion orientations in the $(001)_{Kfs}$ growth sector are also highly systematic (Fig. 10). In contrast to the large single cluster of $(010)^*_{Pl}$ in the $(010)_{Kfs}$ sector, in the $(001)_{Kfs}$ sector there are two main clusters of $(010)^*_{Pl}$, with a weaker one parallel to $(010)^*_{Kfs}$ and a stronger one parallel to $(001)^*_{Kfs}$. There is also a slight concentration of $(010)^*_{Pl}$ within the $(001)_{Kfs}$ plane. The $[010]_{Pl}$ axes have a very similar distribution, but with weaker clustering.

462 $(001)^*_{Pl}$ are tightly clustered parallel to $(001)^*_{Kfs}$. Weaker concentrations of $(001)^*_{Pl}$ lie
463 approximately within the $(001)_{Kfs}$ plane, at $(010)^*_{Kfs}$ and ~55° to either side of it. $[001]_{Pl}$
464 clusters around $[001]_{Kfs}$, especially in the Tuolumne data, with some spread around a small
465 circle ~25° away from $(001)^*_{Kfs}$. $[001]_{Pl}$ are also distributed within the $(001)_{Kfs}$ plane, in two
466 stronger clusters ~30° to either side of $[010]_{Kfs}$ and a weaker, more elongate cluster ~90°
467 away from $[010]_{Kfs}$.
468 $[100]_{Pl}$ lie mostly within the $(001)_{Kfs}$ plane, in a main cluster parallel to $[100]_{Kfs}$ and
469 two weaker clusters ~65° to either side.
470 **Plagioclase inclusions in megacryst $(\bar{2}01)$ growth sectors**
471 $(010)^*_{Pl}$ cluster parallel to $(\bar{2}01)^*_{Kfs}$ (Fig. 11), with a second weaker cluster parallel to
472 $(010)^*_{Kfs}$. The $[010]_{Pl}$ axes feature two clusters, one parallel to $[010]_{Kfs}$ and one at $(\bar{2}01)^*_{Kfs}$.
473 $(001)^*_{Pl}$ are also strongly clustered parallel to $(\bar{2}01)^*_{Kfs}$, with a weak cluster parallel to
474 $(001)^*_{Kfs}$. The $[001]_{Pl}$ axes are relatively scattered, but feature a small cluster parallel to
475 $[001]_{Kfs}$, a weak girdle within the $(\bar{2}01)_{Kfs}$ plane, and a weak concentration within a small
476 circle ~25° away from $(\bar{2}01)^*_{Kfs}$. $[100]_{Pl}$ axes are oriented either parallel to $[100]_{Kfs}$ or within
477 the $(\bar{2}01)_{Kfs}$ plane.
478
479 **Amphibole inclusions**
480 Only our $(001)_{Kfs}$ and $(\bar{2}01)_{Kfs}$ megacryst growth sectors yielded substantial amphibole
481 data. The amphibole orientation distributions are different in these two sectors (Fig. 12). In
482 both sectors, $[001]_{Hb}$ axes form an uneven girdle within the plane of the host face, while
483 $[100]_{Hb}$ axes cluster normal to the host face. In the $(\bar{2}01)_{Kfs}$ sector, $[001]_{Hb}$ are clustered
484 parallel to $[010]_{Kfs}$. The $(100)^*_{Hb}$ clusters are stronger than the $[100]_{Hb}$ clusters in both growth
485 sectors. The $(010)^*_{Hb}$ distributions are scattered. $\{110\}^*_{Hb}$ directions in both growth sectors
486 form a loose cluster around the pole to the host face.

487

488 **Titanite inclusions**

489 As with amphibole, titanite inclusions have distinctive orientation distributions in each
490 megacryst growth sector (Fig. 13). Inclusions in $(010)_{Kfs}$ growth sectors feature a cluster of
491 $\{111\}^*_{Ttn}$ parallel to $(010)^*_{Kfs}$, while those in $(001)_{Kfs}$ growth sectors have $\{111\}^*_{Ttn}$
492 clustered parallel to $(001)^*_{Kfs}$. Both growth sectors also feature minor clusters of $(100)^*_{Ttn}$
493 parallel to the pole to the host face.

494

495 **K-feldspar inclusion**

496 There is one example in the EBSD datasets where a megacryst includes a smaller K-
497 feldspar grain with an orientation distinct from that of the host (Fig. 14). The grain is hosted
498 within the (001) sector of Sample B and is ~0.7 mm long, with irregular patchy zonation in
499 CL (Fig. 14). The (001) face of the inclusion is parallel to that of the host, and its [100] axis is
500 very close to that of the host, but the [001] axis of the inclusion is not aligned with that of the
501 host. The host-inclusion orientation relationship is ~9° away from an ideal Manebach twin
502 relationship.

503

504 **ANALYSIS OF MICROSTRUCTURES AND ORIENTATION RELATIONSHIPS**

505 **Growth of inclusions prior to incorporation**

506 As synneusis is the attachment of crystals that formed separately in magma (Vance
507 1969), the first step in identifying synneusis structures is to establish whether the crystals
508 involved nucleated independently. Heterogeneous nucleation of one crystal on another could
509 produce similar textures (Dowty, 1980), including CORs (e.g., Hammer *et al.,* 2010).

510 In the case of inclusions in K-feldspar megacrysts, there is strong evidence for
511 independent nucleation and growth prior to attachment. Inclusions of all phases except quartz

512 are commonly euhedral, indicating growth in free space unimpeded by neighbouring crystals.
513 Many inclusions contain complete, concentric, symmetrical zones, further evidencing growth
514 surrounded by melt (Fig. 4a, d). Plagioclase inclusions within a given megacryst horizon can
515 feature diverse zonation patterns in CL, suggesting that they grew in separate environments to
516 each other before coming together.
517 Sectioning effects can theoretically result in the appearance of concentric zonation in a
518 crystal that had nucleated heterogeneously on a surface (Dowty 1980). However, in the
519 present dataset this effect can be ruled out in most cases, as the orientations of both the host
520 and the inclusion faces are known. None of the inclusions analysed exhibit the asymmetrical
521 zones expected from heterogeneous nucleation on the surface of the megacryst.
522 There are many examples where the plagioclase crystals are anhedral, with no visible
523 zonation or complex non-concentric zonation, perhaps due to episodes of resorption. It is
524 possible, though not required, that some of these small anhedral crystals nucleated on the
525 megacryst. However, the euhedral inclusions unequivocally formed separately to the
526 megacryst, and euhedral, subhedral and anhedral inclusions commonly occur alongside each
527 other within any given growth zone of a megacryst and display the same CORs with the host
528 (Fig. 8). Therefore, it is most likely that the anhedral inclusions also formed independently in
529 the melt, but experienced resorption prior to attachment. This interpretation is consistent with
530 the extensive evidence of resorption in the megacryst zonation.
531
532 **The role of planar faces**
533 It is typically assumed that crystals attach by synneusis when their large, flat faces
534 come into contact. Such a model could adequately explain the titanite orientation
535 distributions, where a major face such as {111} or (100) is commonly parallel to the
536 megacryst face to which the inclusion attached. Some amphiboles have a large {110} face

parallel to the host face. Most plagioclase inclusions have either (001) or (010) parallel to the host face, and because (001) and (010) are commonly large crystal faces in feldspars, this parallelism could arise when two euhedral crystals meet on their major faces.

However, the joining of planar faces is not an entirely satisfactory explanation for the CORs. Both the megacrysts and the inclusions frequently do not have planar faces, even when their orientation relationships are systematic. The megacryst zones feature rounded corners, wavy boundaries and embayments, and many of the inclusions are subhedral or anhedral. In addition, even inclusions with large, planar faces are not always in a perfect COR with the host crystal. Just like anhedral crystals, the euhedral crystals sometimes have imperfect or random orientations. Crystals therefore appear to attach to each other with systematic CORs independently of having large, flat faces.

Figure 15 illustrates modelled axes distributions for feldspar-feldspar attachments if the only constraint were alignment of the (001) and (010) faces. We model the inclusion as monoclinic for simplicity, but triclinic, albite-twinned plagioclase would result in some of the lines splitting into two parallel lines separated by a few degrees, an effect that contributes to apparent scatter in the observed data. The figure illustrates that a geometric control on orientation due solely to the meeting of crystal faces would generate smooth girdles. Although there is some resemblance between the model (Fig. 15) and the data (Fig. 9 and 10), importantly, the axes in the data cluster strongly within the predicted girdles.

In summary, the presence of planar faces is not required for synneusis to occur, and attachment on planar faces alone cannot account for all characteristics of the data. The inclusion orientations therefore appear to be controlled at least in part by lattice effects and the minimisation of interfacial energies.

Feldspar twin laws control plagioclase inclusion orientations

Previous researchers have disagreed about whether plagioclase inclusions in K-feldspar display crystallographic preferred orientations, or simply shape preferred orientations. Several early studies suggested crystallographic alignments (Vance, 1969 and references therein). However, Dowty (1980) reported that "in most cases there is no systematic crystallographic alignment other than parallelism of the faces; and the only face of attachment of the plagioclase seems to be (010)". The latter point is not consistent with our data, as the plagioclase inclusions also routinely attach to megacrysts on $(001)_{Pl}$ (Fig. 9, 10 and 11). We will now address the former claim that there is no systematic crystallographic alignment.

The crystal axes of the inclusions exhibit strong clustering (Fig. 9, 10) within the girdles allowed by parallel alignment of faces (Fig. 15), strongly suggesting a crystallographic control on the orientations of the inclusions. In this section, we will demonstrate that the orientation clusters can be explained by the interplay of three influences: the identities of the host and inclusion attachment planes, twinning within included plagioclase grains, and the attachment of plagioclase to K-feldspar in specific preferred orientations. We will discuss each of the common feldspar twin laws to explain how they underpin the clusters in the orientation data. The identified feldspar orientation relationships are summarised schematically in Fig. 17.

In the pole figures we follow the convention for triclinic minerals and present plagioclase axis data without antipodal symmetry, although the megacryst reference frame and the plagioclase polysynthetic twinning effectively symmetrise the $[100]_{Pl}$ and $[001]_{Pl}$ data such that every cluster in the upper hemisphere has a lower-hemisphere counterpart. For simplicity, the modelled twin orientations in Fig. 16 are illustrated using orthoclase lattice parameters and antipodal symmetry. Plagioclase lattice parameters would result in some

lattice directions being a few degrees away from the modelled orientations, but the fundamental findings are unaffected.

Albite and pericline

Albite and pericline twin laws (180° about (010)* and [010] respectively) are symmetrically invalid for monoclinic feldspars, but occur as polysynthetic twins within the included plagioclases. Therefore, some of the data clusters comprise two sub-clusters separated by a few degrees, due to albite/pericline twins superimposed on the other orientation relationships described below.

Parallel attachment

Parallel attachment is the lowest energy orientation for the joining of two crystals of the same mineral by synneusis, and is normally by far the most common (Vance, 1969). The data are consistent with this statement also being true for synneusis between plagioclase and K-feldspar; the strongest clusters in the plagioclase pole figures are typically parallel to the same crystal direction in the host megacryst. In the Tuolumne data from the (001) growth sector (Fig. 10), $[010]_{Pl}$ are skewed to the upper hemisphere, parallel to $[010]_{Kfs,}$ instead of $[0\bar{1}0]_{Kfs}$ which lies in the lower hemisphere of our reference frame, suggesting a preference for parallel alignment. The $(\bar{2}01)_{Kfs}$ sectors are an exception, perhaps because it is unfavourable for plagioclase crystals to attach to K-feldspar on $(\bar{2}01)_{Pl}$ as would be required to facilitate parallelism. Plagioclase usually attaches on $(010)_{Pl}$ or $(001)_{Pl}$ even on $(\bar{2}01)_{Kfs}$.

Manebach and Ala

The Manebach law involves a 180° rotation about (001)* while the Ala laws involve 180° rotations about [100]. The laws result in the same orientation relationship in monoclinic

feldspars, which we will henceforth refer to as the Manebach relationship for simplicity. An inclusion attaching to a megacryst with a Manebach relationship would have $(010)_{Pl}$ and $(001)_{Pl}$ parallel to those of the megacryst, regardless of whether it attached to $(010)_{Kfs}$ or $(001)_{Kfs}$ (Fig. 16). Manebach relationships may therefore be likely synneusis relationships for meetings of both $(001)_{Pl}$ on $(001)_{Kfs}$, and $(010)_{Pl}$ on $(010)_{Kfs}$

The Manebach law leaves the [100] and [010] axes parallel to their original positions but results in a ~52° anticlockwise offset of $[001]_{Pl}$ in our reference frame (Fig. 16). There is elevated data density here (Fig. 9, 10), but it is not very pronounced. Consider a meeting of $(001)_{Pl}$ and $(001)_{Kfs}$. A 26° circle of possible positions is available to $[001]_{Pl}$ but in most cases the inclusion attaches with $[001]_{Pl}$ parallel to $[001]_{Kfs}$. More rarely, it may attach in a Manebach relationship, and more rarely still, in a random orientation within the restriction of parallelism of $(001)_{Pl}$ and $(001)_{Kfs}$. Likewise, in the $(010)_{Kfs}$ sectors $[001]_{Pl}$ are usually parallel to $[001]_{Kfs}$ and more rarely in a Manebach position. Manebach attachments are therefore possible, but rare.

Carlsbad and X law

The Carlsbad law involves a rotation of 180° around [001], and the X law is a 180° rotation around (100)* (Fig. 16). As before, the two laws have the same outcome for monoclinic feldspars, which we will refer to as a Carlsbad relationship. A Carlsbad relationship brings neither $(001)_{Pl}$ nor $(010)_{Pl}$ parallel to $(001)_{Kfs}$, therefore we expect no Carlsbad attachments to $(001)_{Kfs}$, and indeed the data exhibit no elevated occurrence of Carlsbad relationships (Fig. 10). In contrast, the Carlsbad relationship is very common in the $(010)_{Kfs}$ data, as evidenced by the $[100]_{Pl}$ clusters that are offset by ~56° clockwise from $[100]_{Kfs}$ (Fig. 9). The relationship is favourable in the $(010)_{Kfs}$ growth sector because a Carlsbad relationship would bring $(010)_{Pl}$ parallel to $(010)_{Kfs}$.

636

637 *Baveno*

638 The Baveno laws merit particular attention. They involve a 180° rotation around (021)*
639 for the Baveno right law, and $(0\bar{2}1)$* for the Baveno left law; the composition plane in alkali
640 feldspars is typically (021) or $(0\bar{2}1)$ respectively. For the feldspars in this study, Baveno
641 relationships effectively bring (010) of one twin parallel to (001) of the other twin (Fig. 16)
642 and can be visualised as 90° rotations around [100]. Baveno twins are rare in plagioclase
643 (Deer *et al.*, 2013).

644 Because (010) and (001) are commonly large faces in plagioclase, it has repeatedly
645 been hypothesised that synneusis of plagioclase should involve meetings on these faces,
646 producing Baveno-like twins with distinctive (010) on (001) composition planes that would
647 not be expected to result from growth processes (Vance, 1969; Dowty, 1980). Indeed, Dowty
648 (1980) used the scarcity of such relationships to argue that synneusis is rare or non-existent in
649 plagioclase. However, in the megacrysts, Baveno relationships between the host and its
650 inclusions are very common.

651 Plagioclase inclusions attaching to $(001)_{Kfs}$ on $(010)_{Pl}$ geometrically cannot have their
652 [001] or [010] axes aligned, but can align their [100] axes in a Baveno relationship, and the
653 data show that this is common (Fig. 10). The two $[001]_{Pl}$ clusters within the $(001)_{Kfs}$ plane
654 (Fig. 10) match the expected Baveno positions (Fig. 16). The Baveno relationship also results
655 in $(001)^*_{Pl}$ clustering parallel to $(010)^*_{Kfs}$ even though in this sector, inclusions are not in
656 contact with the megacryst (010) face (Fig. 10).

657 Plagioclase inclusions attaching to $(010)_{Kfs}$ on $(001)_{Pl}$ also geometrically cannot have
658 their [001] or [010] axes aligned, but can align their [100] axes in a Baveno relationship. This
659 relationship would manifest as clustering of the $[001]_{Pl}$ axes in particular positions within the
660 26° small circle around (001)* of the megacryst (Fig. 16), which is evident in the data (Fig.

9). In the lower hemisphere of the SP data, there are four clusters within the 26° small circle and the lower-left and upper-right of these result from the two Baveno laws. The other two clusters will be discussed in the next section. Baveno relationships should also produce an incidental cluster of $(010)^*_{Pl}$ parallel to $(001)^*_{Kfs}$, and this cluster is present in the data (Fig. 9). We can conclude that the Baveno relationship is a favourable relationship both for inclusions attaching to $(001)_{Kfs}$ on $(010)_{Pl}$, and for those attaching to $(010)_{Kfs}$ on $(001)_{Pl}$.

Combined Baveno and Carlsbad relationships

Some of the clusters in the data cannot be explained by the operation of a single twin law, but can be explained by combined twin laws. In the $(001)_{Kfs}$ growth sector data (Fig. 10), there are prominent clusters of $[100]_{Pl}$ and $(001)^*_{Pl}$ that are consistent with attachment of inclusions on their $(010)_{Pl}$ faces (Fig. 10), but are not consistent with Baveno laws (Fig. 16). These orientations can be reproduced by applying a Baveno rotation followed by a Carlsbad rotation (Fig. 16, column 3).

In the $(010)_{Kfs}$ growth sector (Fig. 9), there are similarly unexplained clusters, both within the 26° small circle of $[001]_{Pl}$, and in the $[010]_{Pl}$ data clockwise from $[001]_{Kfs}$ (Fig. 9). We can reproduce these clusters from a Carlsbad rotation followed by a Baveno rotation (Fig. 16, column 2).

The abundance of combined twin relationships in the data prompt the question of whether such relationships arise due to the attachment of plagioclase inclusions with internal Carlsbad or Baveno twins. This mechanism is unlikely for two reasons: firstly, that Baveno twins are rare in plagioclase (Deer *et al.*, 2013); and secondly, that attachment of internally twinned plagioclase fails to explain why Carlsbad-Baveno relationships are dominant within the $(010)_{Kfs}$ sector while Baveno-Carlsbad relationships dominate the $(001)_{Kfs}$ data. In contrast, if the relationships result from the attachment of individual crystals, a simple explanation emerges: Carlsbad-Baveno relationships result in a $(001)_{Pl}$ plane parallel to

686 $(010)_{Kfs}$ but no major plane parallel to $(001)_{Kfs}$ and therefore are only viable synneusis
687 relationships in the $(010)_{Kfs}$ growth sectors. Likewise, a Baveno-Carlsbad relationship
688 produces $(010)_{Pl}$ parallel to $(001)_{Kfs}$ and is therefore viable for the $(001)_{Kfs}$ growth sectors, but
689 produces no plane parallel to $(010)_{Kfs}$ so would be non-viable for $(010)_{Kfs}$ growth sectors. The
690 combined relationships are therefore genuine synneusis relationships between the megacryst
691 and its inclusions. This conclusion is notable because combined Baveno and Carlsbad
692 relationships have not been reported as growth twins, so may be diagnostic of synneusis.
693
694 *Three-law relationships*
695 Only a few minor clusters in the plagioclase orientation distributions of the $(010)_{Kfs}$ and
696 $(001)_{Kfs}$ growth sectors remain unexplained. These remaining clusters can be reproduced by
697 applying three successive rotations away from the megacryst orientation. Three-law
698 relationships have not, to our knowledge, been reported as growth twins and are probably
699 unique to synneusis scenarios. There is no inherent reason why a combination of three twin
700 law rotations should result in a low-energy orientation relationship, therefore the only
701 relationships considered here are those suggested by the data.
702 In the $(010)_{Kfs}$ sector (Fig. 9), there is small $[001]_{Pl}$ cluster 56° clockwise of $[001]_{Kfs}$,
703 seen most clearly in the Tuolumne data, that remains unexplained. The cluster can be
704 reproduced by a Carlsbad rotation followed by two Baveno rotations (either right then left, or
705 left then right; the outcome is the same), producing an orientation with $(010)_{Pl}$ parallel to
706 $(010)_{Kfs}$ but with a distinctive $[001]_{Pl}$ position (Fig. 16, column 4).
707 In the $(001)_{Kfs}$ sector, the situation is more complex. There are two $(010)_{Pl}$ clusters
708 within the $(001)_{Kfs}$ plane, offset by 56° either side of $[010]_{Kfs}$ (Fig. 10). These clusters require
709 a Baveno rotation, then a Carlsbad rotation, then a second Baveno rotation. There are four
710 viable combinations to explain the clusters: Baveno left-Carlsbad-Baveno right, Baveno left-

711 Carlsbad-Baveno left, Baveno right-Carlsbad-Baveno right, and Baveno right-Carlsbad-
712 Baveno left. All these combinations produce orientations with $(001)_{Pl}$ parallel to $(001)_{Kfs}$ (Fig.
713 16, column 4) and are therefore viable synneusis relationships within the $(001)_{Kfs}$ growth
714 sector. Further evidence of these relationships is present in the 26° small circles formed by
715 $[001]_{Pl}$, in which a pair of faint clusters (Fig. 10; clearest in the Tuolumne data, upper
716 hemisphere) correspond to the modelled Baveno-Carlsbad-Baveno orientations (Fig. 16).
717
718 *Attachments where no twin law is geometrically viable*
719 For an inclusion attaching to the megacryst $(\bar{2}01)_{Kfs}$ face on $(010)_{Pl}$ or $(001)_{Pl}$, there are
720 no viable twin laws. The inclusion may achieve parallelism with the host by attaching on
721 $(\bar{2}01)_{Pl}$, which some inclusions do, but many inclusions instead attach on their more
722 prominent planes (Fig. 11). It is geometrically possible for an inclusion attaching to $(\bar{2}01)_{Kfs}$
723 on its $(001)_{Pl}$ to have $[010]_{Pl}$ parallel to $[010]_{Kfs}$ and the inclusions display a strong preference
724 for this relationship within the available girdle (Fig. 16). This propensity suggests that
725 synneusis pairs prefer specific low-energy orientations even where no twin laws are
726 geometrically viable.
727
728 **Imperfect attachment of a K-feldspar inclusion**
729 Only one candidate inclusion of K-feldspar was found, in Sample B (Fig. 14),
730 suggesting that small K-feldspar crystals did not frequently attach to larger ones by
731 synneusis. However, there may be sample bias as we avoided irregularly shaped megacrysts
732 that may have resulted from synneusis of K-feldspar crystals.
733 Monomineralic crystal clusters can potentially arise from growth twinning (Dowty
734 1980) but in the particular case of the inclusion in Sample B, given the apparent size
735 difference between host and inclusion, the position of the inclusion, the zonation textures and

736 the morphology of their contact, it seems unlikely that they are the product of a twinned
737 nucleus. The orientation relationship between the two grains is approximately 9° away from a
738 Manebach twin (Fig. 14). Given that both crystals are the same mineral, a growth twin would
739 be expected to obey the twin law perfectly (unlike the near-twins typical of plagioclase and
740 K-feldspar pairs, where perfect alignment is not possible).

741 Heterogeneous nucleation cannot be ruled out by the zonation, which is irregular in CL
742 (Fig. 14), but nucleation of a crystal on a substrate of the same mineral, known as
743 homoepitaxy, typically involves perfect parallel alignment (Holness *et al.*, 2023). Nucleation
744 in an orientation misaligned from a twin relationship by 9° would be energetically
745 unfavourable.

746 It is therefore more likely that the inclusion attached by synneusis in an imperfect
747 orientation, reminiscent of the imperfect synneusis attachments observed by Dyck (2023) in
748 quartz. The forces driving the inclusion into a perfect orientation may not have been able to
749 act to completion prior to overgrowth and engulfment by the host. Engulfment prior to
750 perfect alignment could also account for some of the scatter in the plagioclase orientation
751 distributions.

752 One interesting feature revealed by CL is that the included K-feldspar grain has a neck-
753 like structure visible in the zones of the host crystal (Fig. 14), as though during an episode of
754 resorption it stood proud of the surface of the host on a small pedestal. The inclusion also has
755 a rounded morphology, with truncation of its internal irregular zones. The presence of a
756 rounded shape paired with a neck is consistent with the model of Dyck (2023) in which
757 synneusis attachment occurs by paired neck growth and grain rotation. In that model, the
758 material to form the neck is scavenged from the surfaces of the crystals, which rounds off the
759 crystal surfaces (Dyck, 2023). The rounded shape of the inclusion is also consistent with a
760 dissolution-reprecipitation ripening process, whereby larger grains grow at the expense of

761 smaller grains (Mills and Glazner, 2013). Such a process could perhaps explain why the small
762 grain was overgrown by the larger one, rather than both grains continuing to grow at an equal
763 rate, if the large grain was stable and growing while the smaller one was dissolving.

764 **Amphibole orientations**

765 The amphibole pole figures (Fig. 12) do not feature clusters as tight as those found in
766 the plagioclase data, although systematic relationships are still present. The weaker
767 relationships are consistent with the fact that amphibole does not have as much in common
768 with the K-feldspar crystal structure as does plagioclase. Another likely source of scatter is
769 that amphibole frequently occurs in crystal clusters, both within the megacrysts and in the
770 groundmass. Such clusters appear to have formed prior to incorporation into the megacryst
771 (e.g., the cluster top centre of Fig. 5). As only part of each cluster could have come into
772 contact with the megacryst surface, some of the amphibole orientations present in the dataset
773 will not represent direct synneusis relationships with the host megacryst.

774 The amphibole inclusions are typically euhedral and elongate along [001], and [001]
775 commonly lies within the plane of the host face onto which they attached (Fig. 12). It is
776 tempting to interpret this as the product of simple magmatic flow alignment, but in the
777 $(\bar{2}01)_{Kfs}$ sector the amphibole [001] axes cluster around $[010]_{Kfs}$ (Fig. 12). $[010]_{Kfs}$ is
778 geometrically the shortest axis of the feldspars in this study, in common with most feldspars.
779 The fact that the longest axes of the amphiboles are aligned with the shortest axes of the K-
780 feldspars is not readily reconcilable with an origin from flow alignment alone.

781 The amphibole crystals have prominent (110) and $(1\bar{1}0)$ faces, which are related by
782 symmetry and are plotted together in the pole figures. This consideration is important for the
783 interpretation of the apparently dispersed clusters of {110}* in the pole figures. Any
784 amphibole crystal attaching to the megacryst on its (110) face has a related $(1\bar{1}0)$ face with a
785 pole that plots ~60° away from that of the attachment plane, and vice versa. Both {110}*

poles are included in the pole figure, contributing to the apparent dispersion (Fig. 12). Nonetheless, both EBSD and petrographic observations confirm that amphiboles do sometimes attach on their {110} faces. The attachment is generally imperfect, as demonstrated by the breadth of the {110}* clusters parallel to each of the poles of the megacryst attachment faces.

Both EBSD data and petrographic observations suggest that the amphiboles also commonly attach on their (100) planes, which form small and poorly developed faces (Fig. 5) that are often rounded off or absent altogether. It is unexpected for the crystals to attach on these small, irregular faces instead of the much larger and flatter {110} faces. A possible explanation for this phenomenon can be found by returning to the idea that synneusis in favourable orientation relationships occurs to minimise surface energies. Large planar faces are typically slow-growing and stable, whereas small faces are faster-growing and less stable. It is therefore conceivable that in some cases, the greatest energy minimisation may be achieved via attachment of a higher-energy smaller face. Another, related option is that the rounded-off corners, in place of the (100) planes, are molecularly rough surfaces with a greater spatial density of free bonds and greater potential to bond to the megacryst surface.

Titanite orientations

Titanite orientations are relatively systematic, and can be adequately explained by geometrical effects whereby the large planar titanite faces come into parallelism with the host face prior to engulfment. There is no particular evidence to suggest further rotation due to the minimisation of interfacial energies. This lack of rotation may be because titanite and K-feldspar simply have very different lattices, where rotation does not result in large energy savings. Alternatively, the low-energy positions may be incompatible with the typical {111}-dominated habit of titanite, which is ubiquitous in our samples. The most significant

811 crystallographic directions and features (e.g., the TiO_6 octahedra chains) do not lie within the
812 {111} faces and so no amount of rotation around {111}* will bring them into parallelism with
813 crystallographic features of the host face.

814 **Magnetite orientations**

815 Magnetite inclusions that have precipitated in feldspars have previously been reported
816 to display extremely systematic orientation relationships with their host crystals, due to the
817 alignment of features between the two lattices in low-energy orientations (e.g., Ageeva *et al.*,
818 2020). While existing research focuses on plagioclase, similar low-energy orientation
819 relationships between K-feldspar and magnetite almost certainly exist. However, we found no
820 evidence of specific CORs between magnetite and K-feldspar.

821 There may simply not be a large enough energetic difference between systematic and
822 random attachment of magnetite to result in a measurable preferred orientation relationship in
823 the context of synneusis. Magnetite grains also tend to be equant, so are not prone to shape
824 alignment in the same way as titanite. The magnetite inclusions also commonly occur
825 spatially clustered with amphibole and other minerals, which may have arrived at the K-
826 feldspar surface already in a fixed configuration.

827

828 **INTERPRETED PROCESSES**

829 Synneusis requires several steps: the independent nucleation and growth of crystals;
830 processes to bring the crystals together; and processes to attach the crystals together in the
831 orientations that we have observed. We have established that the crystals initially grew
832 independently; we will now discuss crystal convergence, attachment and rotation
833 mechanisms.

834

Crystal convergence

Independently formed crystals must come together in order to attach by synneusis, so synneusis is commonly considered diagnostic of relatively low-viscosity magma through which crystals can easily move, for example due to settling (e.g., Vance, 1969; Jocelyn and Pidgeon, 1974). However, since K-feldspar megacrysts grow in viscous, silicic magmas at moderate crystallinities (Gordon and Wallis, 2024) it is worth critically assessing whether significant differential motion of crystals is necessary, or whether the oriented inclusions could arise from the re-orientation and incorporation of neighbouring crystals encountered by the growing megacryst in a quiescent, effectively static magma.

Phase equilibria modelling suggests that the magma was ~35–55% crystalline during megacryst growth (Gordon and Wallis, 2024), but the megacrysts only contain ~10% inclusions by volume, therefore not all crystals encountered by the growing megacryst were incorporated. Rejection from the megacryst appears to be insensitive to mineralogy: the magma at the time would have comprised ~30–40% plagioclase and <5% mafic and accessory minerals, with little or no quartz, consistent with the relative abundances of the minerals as inclusions. There is no textural evidence of haloes of rejected crystals around the megacrysts, therefore some crystals must have been transported away by moving magma. Megacryst growth in a flowing magma is therefore required; this is consistent with field observations of megacrysts showing alignment with magmatic fabrics and evidence of physical accumulation (e.g., Vernon, 1986; Paterson *et al.*, 2005). A variety of processes likely contributed to the magmatic flow over the lifetime of the megacryst, including magma replenishment, convection, and tectonic stress.

858 **Mechanisms of crystal attachment**

859 While magma flow processes could bring crystals together and align neighbouring
860 crystals by shape, some further mechanism is required to account for the observed strongly
861 crystallographic orientation relationships.

862 One possibility is that crystals that serendipitously encounter a megacryst in low-energy
863 configurations are likely to adhere, while unfavourably oriented crystals do not adhere and
864 are transported away by magmatic flow. A second possibility is that unfavourably oriented
865 inclusions are rejected at the megacryst growth front and "pushed" out of the way or rotated
866 into favourable alignments by the force of crystallisation of the megacryst. A third possibility
867 is that inclusions initially attach in imperfect orientations, then rotate due to the minimisation
868 of surface energies.

869 The first two options do not fit well with the observation that megacrysts incorporate
870 crystals of every available mineral, even those that lack strongly favourable CORs and are
871 incorporated in essentially random orientations, such as magnetite. We consider it to be more
872 likely that inclusions of all minerals initially attached to the megacryst in random or weakly
873 systematic orientations controlled by crystal shape and magma flow conditions. Then, due to
874 its crystallographic similarities to the megacryst, plagioclase experienced a strong energetic
875 drive to rotate into crystallographically-controlled orientations.

876

877 **Rotation due to minimisation of interfacial energies**

878 There has been little research on rotation driven by interfacial energy in silicates.
879 However, rotation of neighbouring crystals into low-energy orientations has been directly
880 observed in partially molten alloys, where measurable rotation occurs on timescales of
881 minutes (Dake *et al.*, 2016). Rotation of silicates in magma may be slower, but rotation must

occur rapidly relative to megacryst growth as most plagioclase inclusions attained favourable orientations before engulfment.

Although most plagioclase inclusions lie in preferred orientations, some do not (e.g., Fig. 8). The imperfect inclusions are not concentrated in particular growth zones (Fig. 8), so a dependence on the growth rate of the megacryst is doubtful. Perhaps a more likely explanation is that at the moderate, fluctuating crystallinities relevant to megacryst growth, ephemeral force chains (Bergantz *et al.*, 2017) occasionally prevented free rotation.

Periodicity of synneusis

Inclusions are more abundant in some concentric zones than in others (Fig. 3). Statistically, synneusis should occur more frequently with increasing crystallinity (Dowty, 1980), until the point at which crystals inhibit free movement of their neighbours (Gordon and Wallis, 2024). Fluctuating crystallinity over time may therefore have exerted some control over the rate of synneusis. Megacryst growth rate may also influence the ratio of inclusions incorporated to crystals rejected, a phenomenon recognised in other crystalline materials including ice (Yemmou *et al.*, 1991).

Episodic attachment of crystals could also have occurred due to variable crystal mobility associated with magma replenishment (Moore and Sisson, 2008). Magma replenishment could promote synneusis by mechanically perturbing the magma and decreasing magma viscosity. The inclusions do not always lie on zone boundaries (see Fig. 4) but the most inclusion-rich zones are typically associated with deeply incised resorption horizons (Fig. 4c), suggesting high rates of synneusis are associated with episodes of resorption.

Resorption and regrowth

Evidence of repeated resorption is ubiquitous in K-feldspar megacrysts. Rhythmic barium zonation and resorption boundaries in megacrysts have previously been attributed to magma replenishment (Słaby *et al.*, 2007; Moore and Sisson, 2008), and analogous textures in anorthoclase megacrysts from Mount Erebus have been ascribed to convection (Moussallam *et al.*, 2015). In the few degrees above the eutectic, K-feldspar undergoes greater changes in modal abundance with temperature than other minerals (Gordon and Wallis, 2024) and therefore small fluctuations in conditions cause greater resorption of K-feldspar than other minerals. Prolonged magma storage buffered at or just above eutectic temperatures therefore creates ideal conditions for the dissolution and reprecipitation of K-feldspar. The resultant coarsening (Mills and Glazner, 2013) is a likely contributor to the megacrysts' exceptional size compared to the other minerals present.

CL maps of the megacrysts reveal two broad categories of megacryst embayments. The first type comprises deep linear or branching embayments, sometimes with zones that record inwards growth of K-feldspar, culminating in a core of quartz (Fig. 4f). The embayments morphologically resemble glassy melt inclusions observed in anorthoclase megacrysts from Mount Erebus in Antarctica (Moussallam et al., 2015) and quartz inclusions in some rapakivi granites (Vernon, 2016). The embayments appear to result from infilling of voids within the megacryst, which formed both via resorption and/or reaction along weaknesses and fractures, and due to the disruption of megacryst growth by inclusions.

The second type of embayment comprises shallower cup-shaped embayments typically containing inclusions (Fig. 4a, c, d). Given that these embayments closely follow the boundaries of the inclusions, we interpret them as having formed by preferential dissolution along grain boundaries during resorption events. Where shallow embayments have no visible inclusion, the inclusion may be out of plane or may have detached following grain-boundary

dissolution. Dissolution on grain boundaries during magma recharge, or "defrosting" of mush, has previously been recognised in similar plutonic rocks (Barnes and Werts, 2022). The presence of mineral impurities on the megacryst surface likely promotes embayment formation instead of smooth or faceted resorption.

Resorption may promote the attachment of crystals to form monomineralic clusters, by creating a localised boundary layer with a composition similar to that of the dissolving crystals, that facilitates attachment (Hogan, 1993). A similar mechanism could operate during the oriented attachment of plagioclase and K-feldspar.

Why do megacrysts have so many inclusions?

K-feldspar megacrysts are unusually rich in inclusions compared to other minerals (Fig. 3). K-feldspar stabilises at ~35% crystallinity in a typical granodiorite (Whitney, 1988; Gordon and Wallis, 2024), and megacrysts grow from nucleation to full size within a small temperature range, over which most other minerals do not undergo as large a change in modal abundance (Gordon and Wallis, 2024). Upon encountering a small crystal, the megacryst will therefore overgrow it, rather than vice versa. The dearth of asymmetrical zones in the inclusions confirms that inclusion growth was negligible during the interval between attachment and engulfment. K-feldspar's propensity for dissolution may also promote synneusis, by creating localised reactive boundary layers and energetically unfavourable irregular surfaces.

While quartz also stabilises late, it crystallises many small crystals instead of a few large ones, making it less likely to engulf its neighbours. K-feldspar also has a more diverse interface chemistry than quartz, perhaps offering greater opportunities to form the bonds necessary for synneusis. Research into quartz-neighbour relationships may provide further insight.

WIDER IMPLICATIONS

Universality of synneusis orientation relationships

Oriented inclusions are a ubiquitous feature of K-feldspar megacrysts, and the similarity between the data from Tuolumne and Separation Point (Fig. 9, 10) demonstrates that the processes governing inclusion attachment are fundamental. Magmatic conditions enhance or inhibit the frequency of synneusis attachments, but do not define the crystallographic orientation relationships.

The strength and distinctiveness of the CORs between K-feldspar and plagioclase (Fig. 17) could facilitate identification of synneusis in non-megacrystic silicic rocks. Particularly promising is the finding that many common synneusis CORs are distinct from the common feldspar growth twins. Baveno-type CORs with (010)/(001) composition planes and the various Baveno-Carlsbad CORs are distinctive relationships that could signal synneusis even where other evidence is inconclusive. The same synneusis CORs may also occur in plagioclase, and further research into plagioclase glomerocryst orientation relationships would be valuable.

Synneusis at high crystallinity

Synneusis has previously been considered characteristic of low-crystallinity magmas (e.g., Schwindinger and Anderson, 1989; Dyck and Holness, 2022). However, synneusis of megacryst inclusions occurred at moderate crystallinities (Gordon and Wallis, 2024), in a magma where viscosity would have been high and the effects of crystal inertia negligible (Glazner, 2014). Synneusis clusters are robust petrological evidence of an environment where relative motion of crystals could occur, but are not necessarily evidence of turbulence, low crystallinity, or low viscosity.

Magma rheology and mush structure

Magma is commonly envisaged as a melt with individual crystals in suspension, but crystals are reactive and we have demonstrated that K-feldspar will attach to neighbours of any mineralogy. Clustering of crystals via synneusis may have profound knock-on effects for the structure, rheology and eruptibility of the magma (Jerram, 2003). If magmas' crystal cargoes comprise irregularly shaped interlocking solid clumps, rather than individual crystals, then this may, for example, increase mush permeability and stabilise melt extraction pathways. Models concerning the physical behaviour of magma may be improved by considering the presence of irregularly shaped crystal clusters.

Identifying polymineralic synneusis in the geological record

While synneusis in megacrysts produces visibly systematic microstructures, polymineralic synneusis in other contexts may generate cryptic textures, where EBSD could prove invaluable for identifying CORs. Polymineralic synneusis CORs likely exist between many common rock-forming minerals, and once the CORs are identified, thin sections can be surveyed with EBSD to search for evidence of synneusis. Mineral pairs with specific low-energy epitaxial CORs, such as clinopyroxene and magnetite (Feinberg *et al.*, 2004; Hammer *et al.*, 2010; Peres *et al.*, 2024) and clinopyroxene and orthopyroxene (Tarney, 1969; Nicholls and Stout, 1997) may be particularly likely to form synneusis CORs. Contextualising CORs with careful microstructural characterisation to differentiate between cluster-forming processes is therefore essential.

CONCLUSIONS

The mineral inclusions in K-feldspar megacrysts attached by polymineralic synneusis. Inclusions of all minerals present in the melt were incorporated into the megacrysts, in orientations initially controlled mainly by shape. Where low-energy orientation relationships were available, the inclusions rotated into them. Plagioclase, being very similar to K-feldspar, displays extremely systematic crystallographically-controlled orientations; amphibole and titanite display weakly systematic orientations; and magnetite inclusions are not systematically oriented.

Plagioclase and K-feldspar form a distinctive suite of orientation relationships. Some relationships reflect feldspar twin laws, while others are distinctive synneusis relationships. Baveno-like relationships with (010)/(001) attachment interfaces are extremely common, and may be characteristic of synneusis. Amphibole forms weaker orientation relationships with K-feldspar, but the relationships cannot readily be explained by geometry-controlled attachment so may also be crystallographically controlled. Titanite and magnetite inclusions do not display crystallographically-controlled orientation relationships with K-feldspar, but titanite has such an anisotropic habit that its geometry-controlled attachment results in characteristic orientation relationships within each megacryst growth sector.

Similar synneusis attachments are likely to be common in igneous rocks, but may be challenging to identify outside of megacrysts. Careful assessment of both orientation relationships and textural features (e.g., zonation patterns) is necessary to discern between synneusis and other cluster-forming processes. EBSD provides emerging opportunities to identify intracrystalline interaction processes including polymineralic synneusis in igneous rocks of any mineralogy.

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DATA AVAILABILITY STATEMENT

All data have been submitted to GFZ Data Services under the title “Microstructural and EBSD data from mineral inclusions in K-feldspar megacrysts”. The DOI is pending and will be provided at the revision stage.

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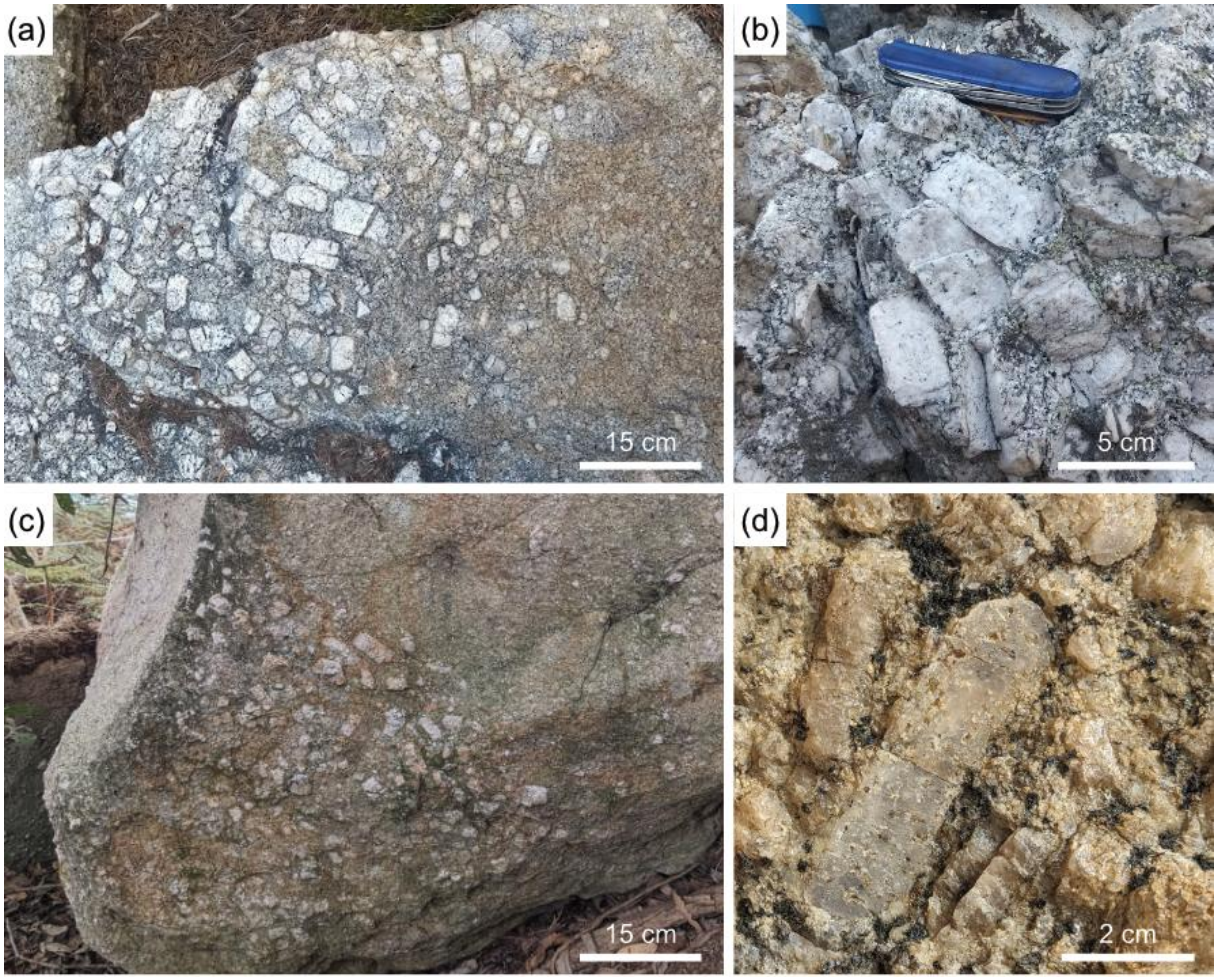


Figure 1: Field photographs of megacrysts in (a, b) Tuolumne Cathedral Peak Granodiorite and (c, d) Separation Point Granite.

Table 1: Sampling localities and EBSD data collection information.

Sample	Pluton	Grid reference (NAD 83)	SEM used for EBSD	EBSD step size
B	pHD	283641 4190262	Zeiss	15 µm
D	pHD/CP contact	284877 4191708	Zeiss	15 µm
G	CP	286173 4193621	Zeiss	20 µm
I	CP	289246 4195221	Zeiss	15 µm
SP2	SP	N/A	Quanta	13 µm

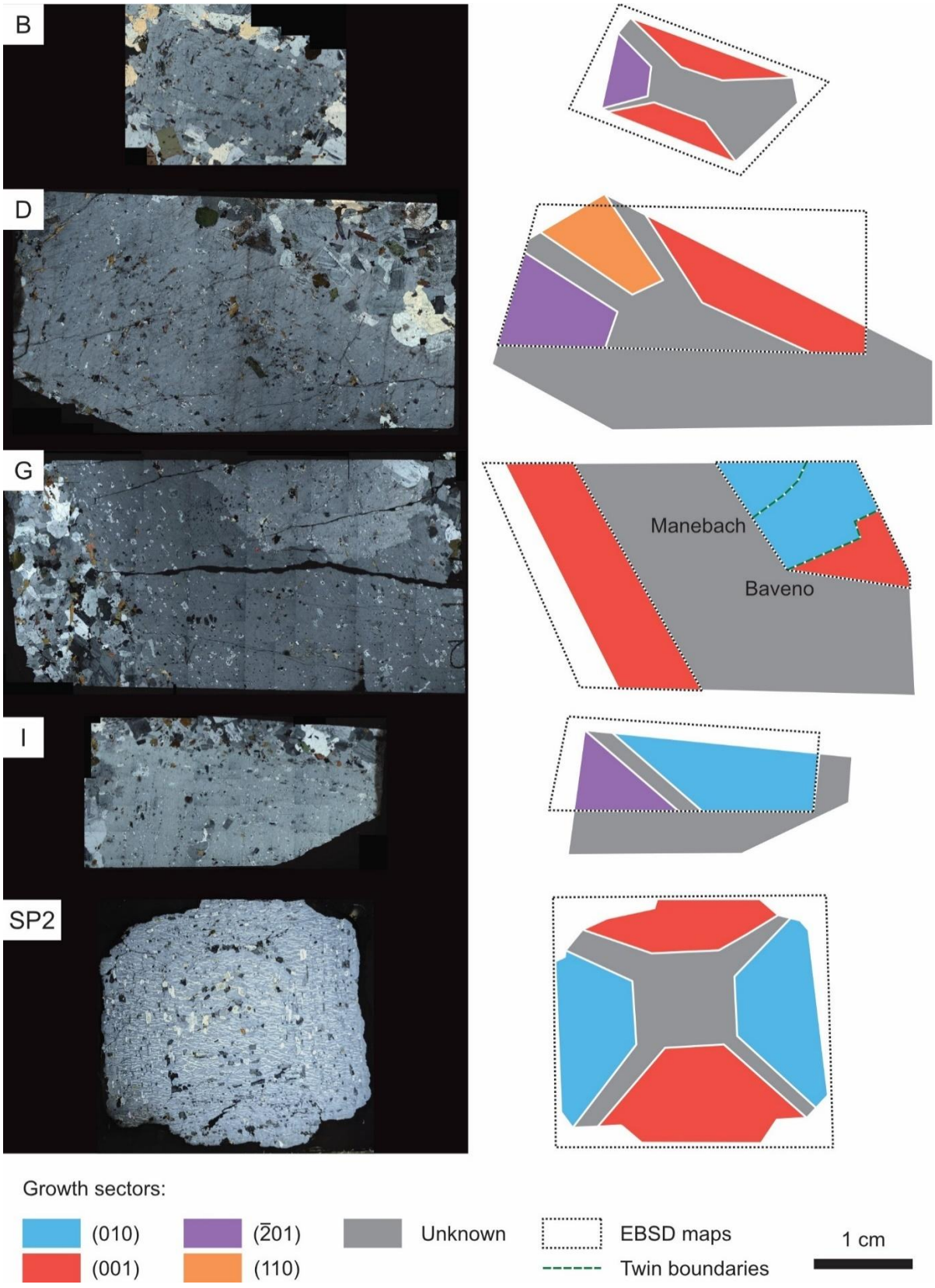


Figure 2: Transmitted light maps (left) and sketches (right) of each of the analysed megacrysts. B, D, G and I are imaged with circularly polarised light; SP2 is imaged with

cross-polarised light. Sketches represent only the euhedral portions of the megacrysts, with the growth sectors colour coded and the EBSD map locations marked.

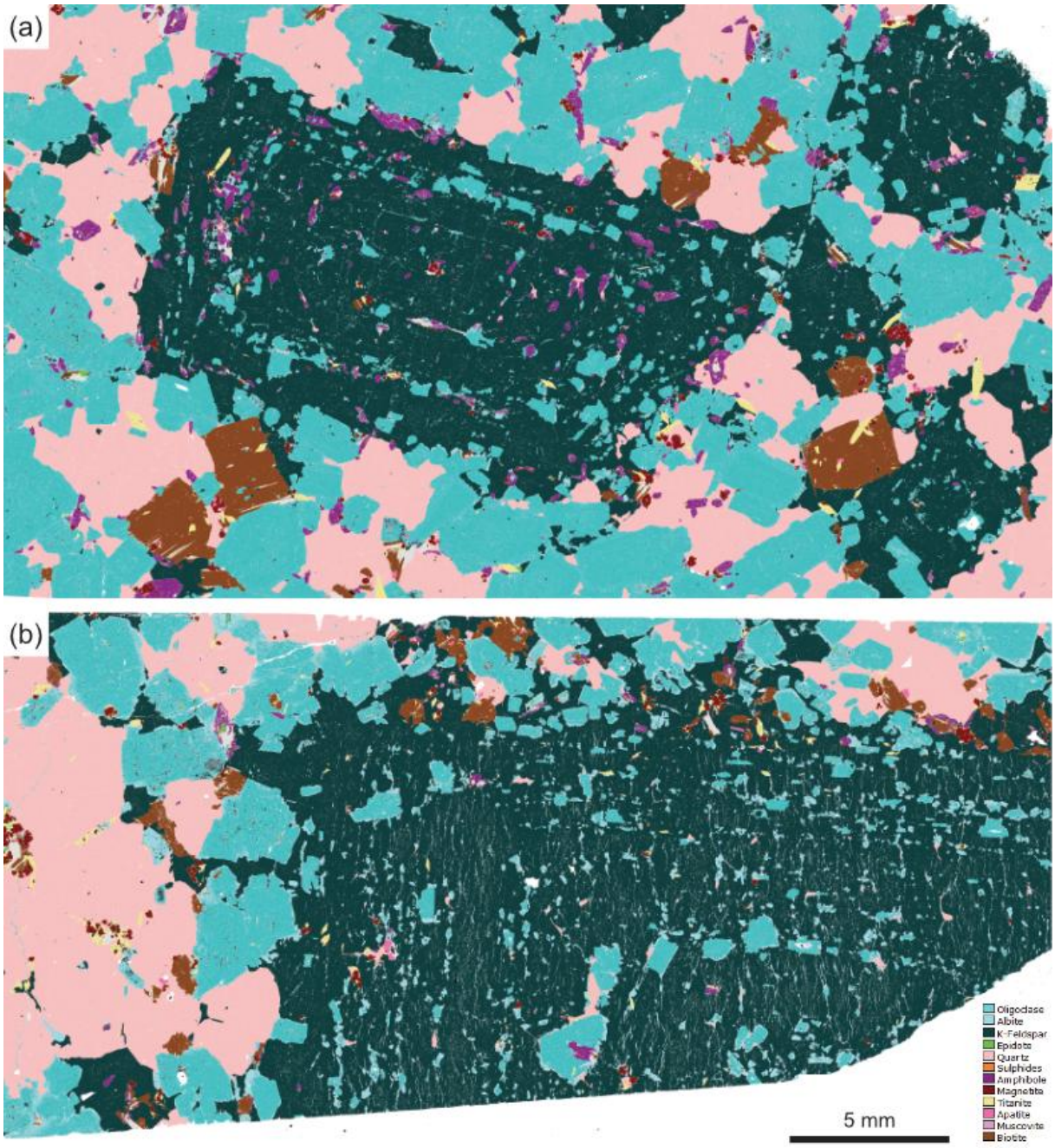


Figure 3: Phase maps of (a) sample B and (b) sample I, showing inclusion distributions.

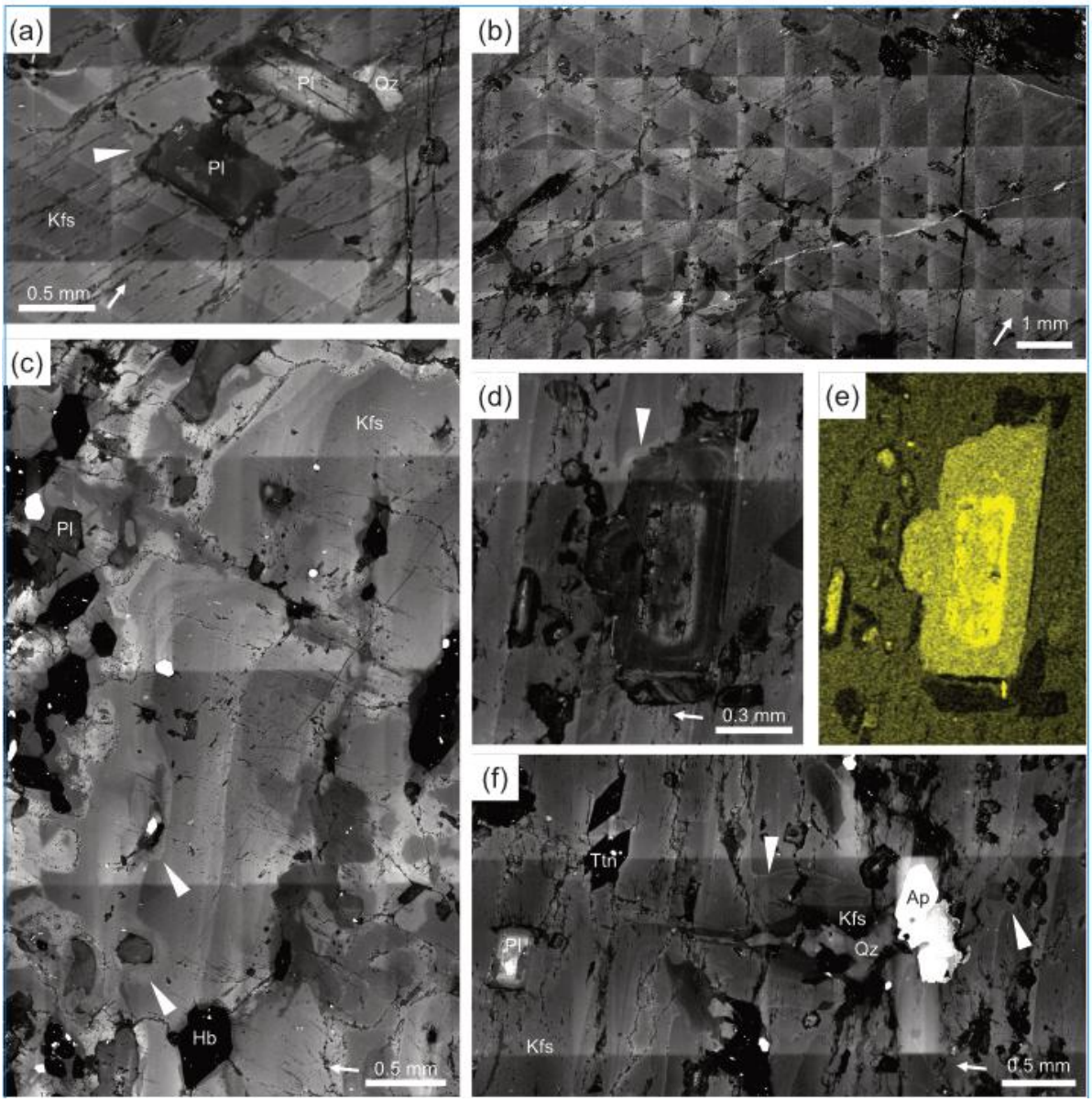


Figure 4: CL images of the megacrysts and their inclusions. Arrows next to scale bars point in the megacryst growth direction. (a) Zoned plagioclase inclusions (shallow embayment arrowed). (b) Typical relatively planar euhedral zones in a megacryst. (c) Resorbed boundaries, including embayments around inclusions (arrowed) and truncation of previous zones (e.g., top right). (d) Zoned plagioclase inclusion with an embayment following its boundary (arrowed) and (e) an EDS calcium map of the same inclusion showing its more calcic core. (f) A deep embayment (arrowed, centre) with a quartz core. Other shallow embayments (example arrowed on right) are also present around plagioclase inclusion grain boundaries.

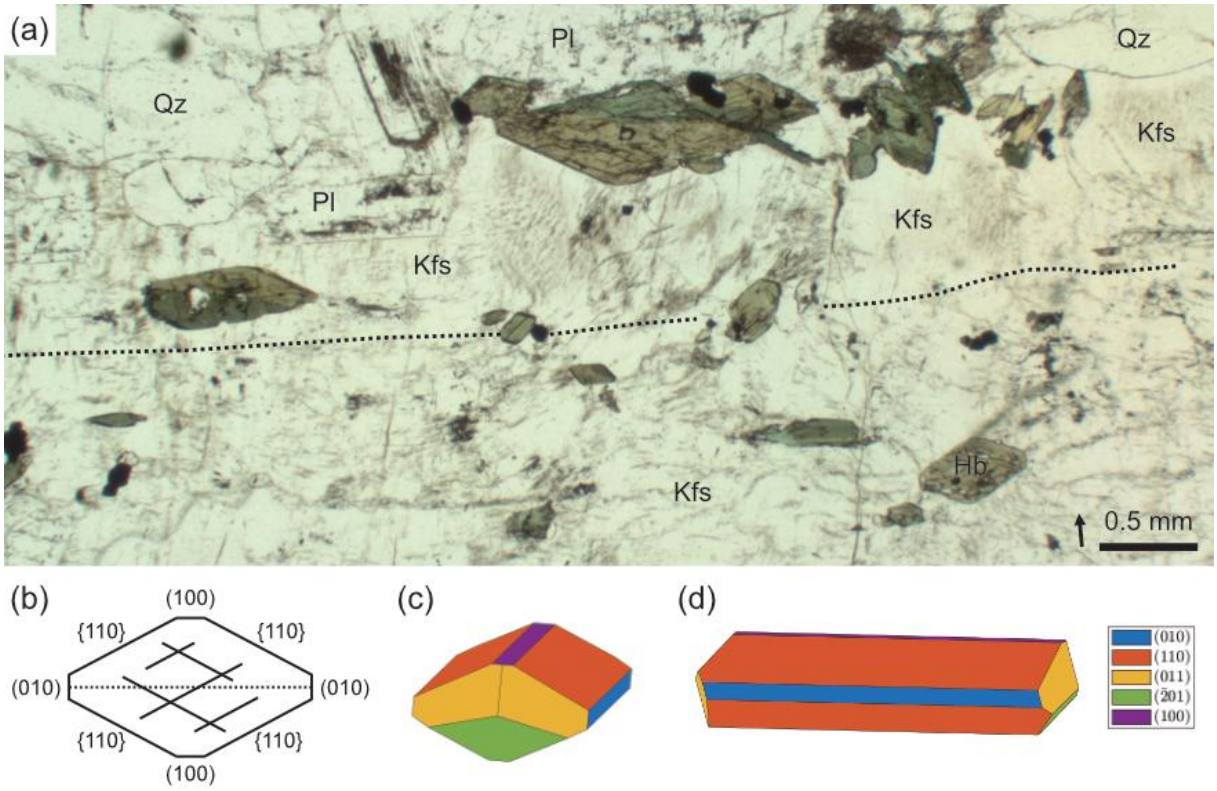


Figure 5: (a) Typical amphibole inclusions (green) in Sample B from pHD. The dashed line marks the outermost major zone boundary visible in CL in the megacryst and the arrow next to the scale bar indicates the growth direction of the megacryst. (b) Schematic cross-section of a typical amphibole looking down [001]. The dashed line is the typical twin plane, (100). {110} cleavages are indicated schematically. Also shown are 3D models of amphibole habits similar to those found in the Tuolumne samples, both (c) looking approximately down [001] and (d) looking approximately down [010] to show elongation along [001].

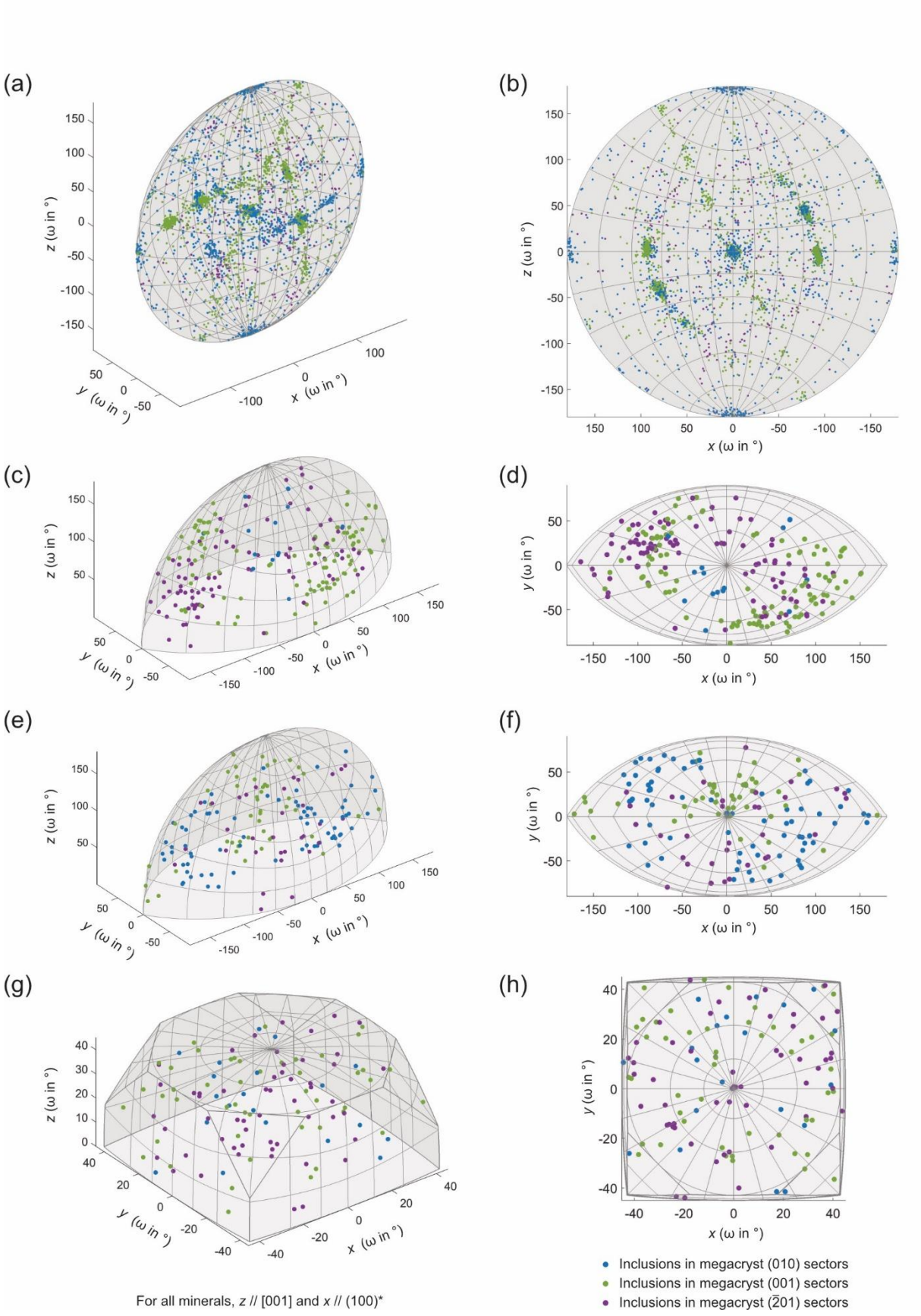


Figure 6: 3D axis-angle plots of the misorientation data between K-feldspar and each inclusion mineral, with fundamental regions shown in light grey and data points coloured by

the megacryst growth sector in which each inclusion is located. ω is misorientation angle. For each plot, an oblique view (left) and a view projected along one axis (right) are shown. (a, b) plagioclase; (c, d) amphibole; (e, f) titanite; (g, h) magnetite.

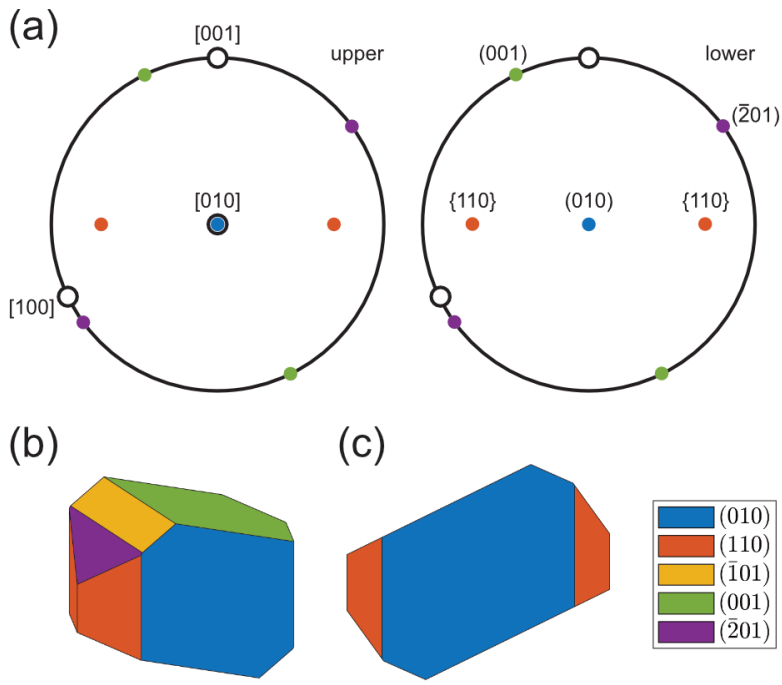


Figure 7: The megacryst reference frame into which the inclusion data were rotated. (a) Pole figure of the K-feldspar axes (labelled in the upper hemisphere) and main planes (labelled in the lower hemisphere). (c) Schematic K-feldspar habit in an arbitrary orientation, showing the main faces. (d) K-feldspar in the reference orientation.

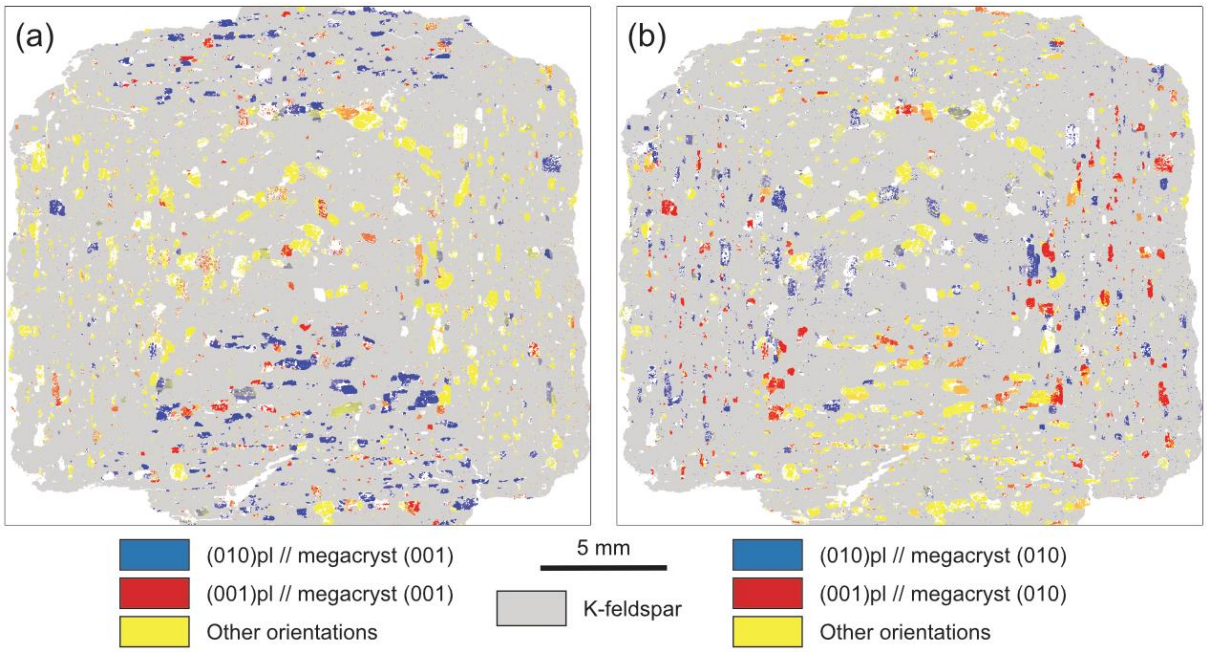


Figure 8: EBSD map of SP2 showing plagioclase coloured by its orientation relationship to the host K-feldspar crystal (in grey), illustrating that plagioclase orientations are arranged in sectors defined by the growth faces of the megacryst. (a) Plagioclase coloured relative to $(001)_{Kfs}$ which are the top and bottom megacryst faces in this map. (b) Plagioclase coloured relative to $(010)_{Kfs}$ which are the side faces in this map (see also Fig. 2).

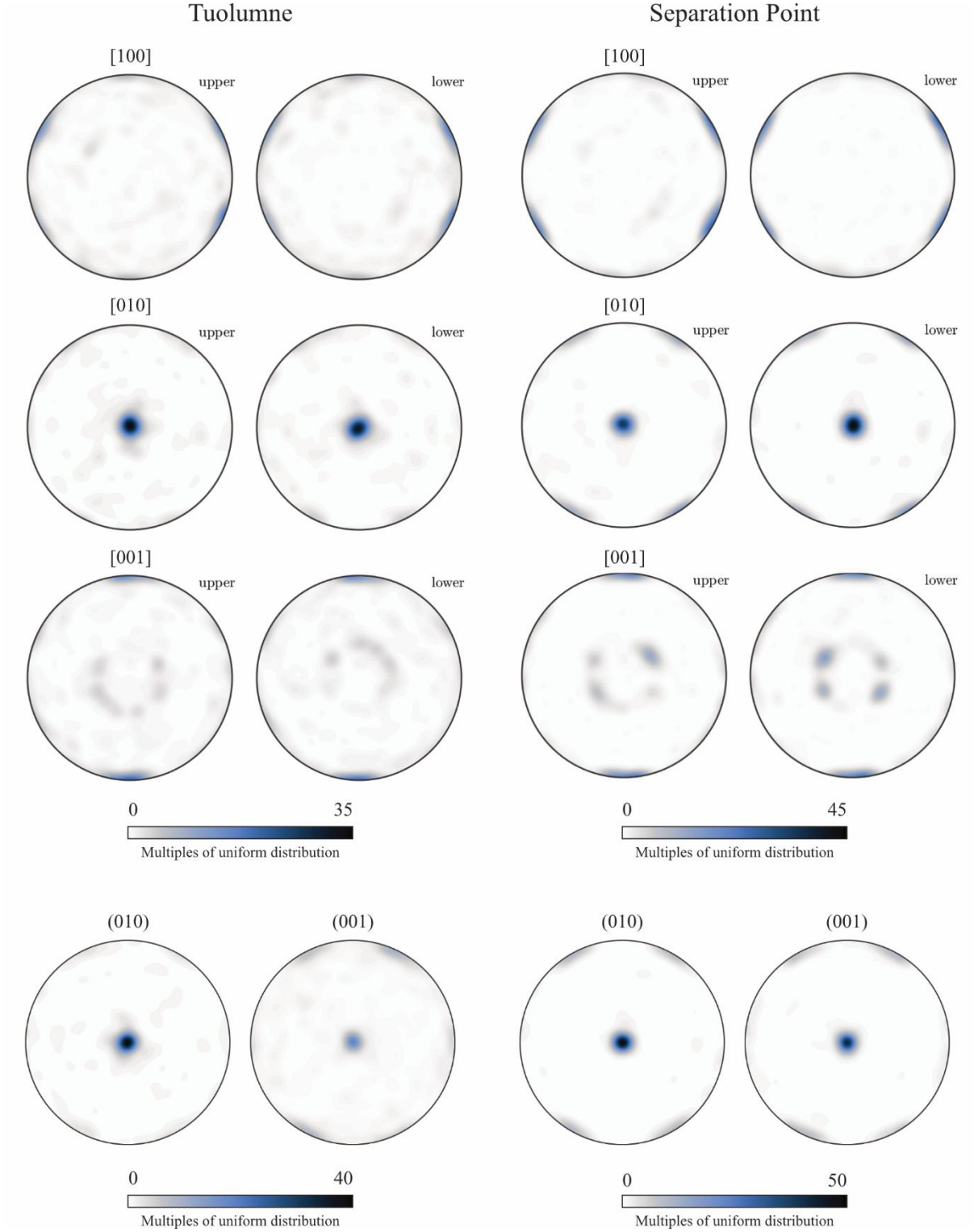


Figure 9: Pole figures of data from plagioclase inclusions in the $(010)_{Kfs}$ growth sectors of megacrysts from Tuolumne (left, n = 742) and Separation Point (right, n = 653) plotted in the K-feldspar reference frame (Fig. 7). We plot both hemispheres for the axes $[100]_{Pl}$, $[010]_{Pl}$ and $[001]_{Pl}$, and the lower hemisphere for poles to the $(010)_{Pl}$ and $(001)_{Pl}$ planes.

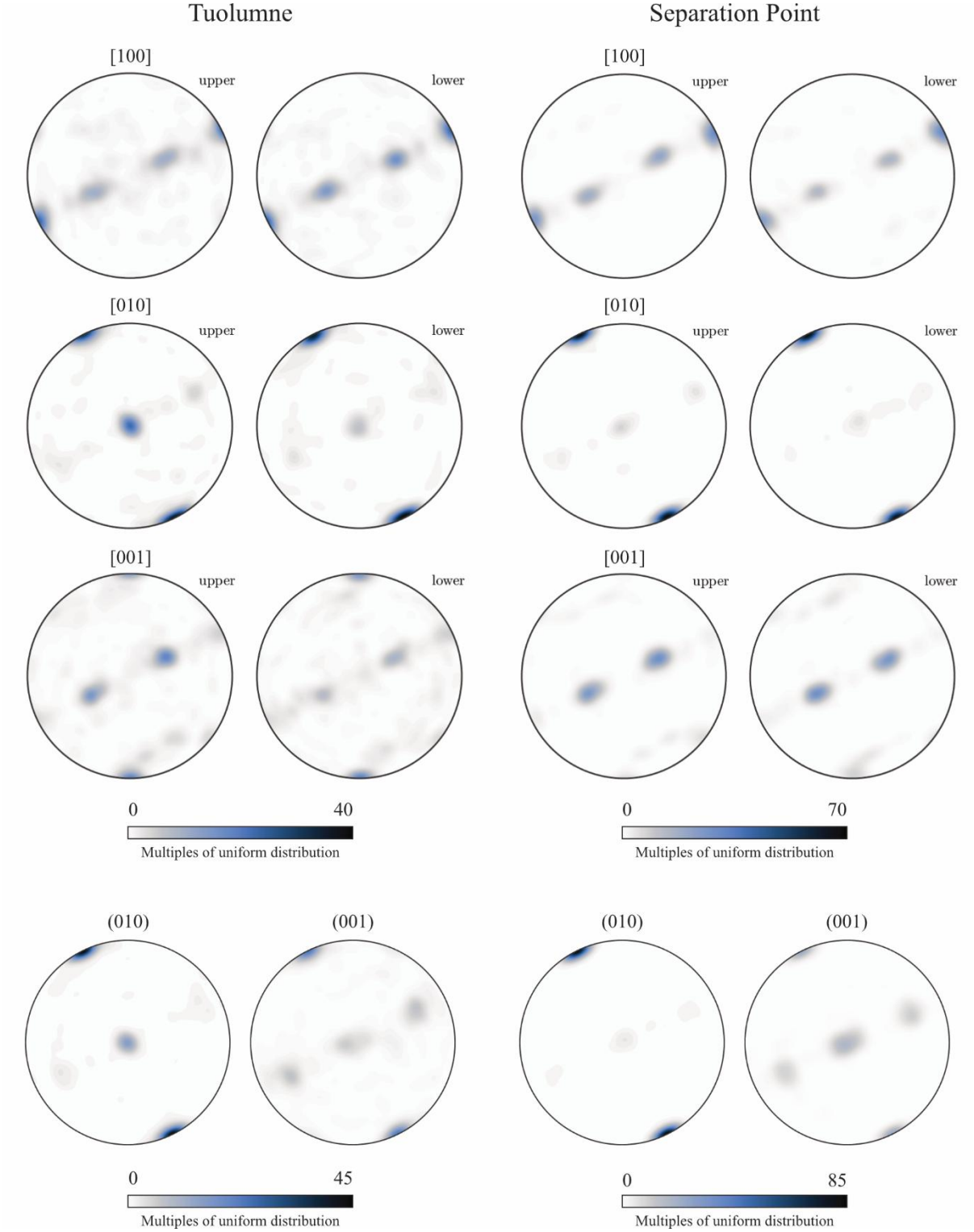


Figure 10: Pole figures of data from plagioclase inclusions in the (001) growth sectors of megacrysts from Tuolumne (left, n = 758) and Separation Point (right, n = 665) plotted in the K-feldspar reference frame (Fig. 7). We plot both hemispheres for the axes $[100]_{Pl}$, $[010]_{Pl}$ and $[001]_{Pl}$, and the lower hemisphere for poles to the $(010)_{Pl}$ and $(001)_{Pl}$ planes.

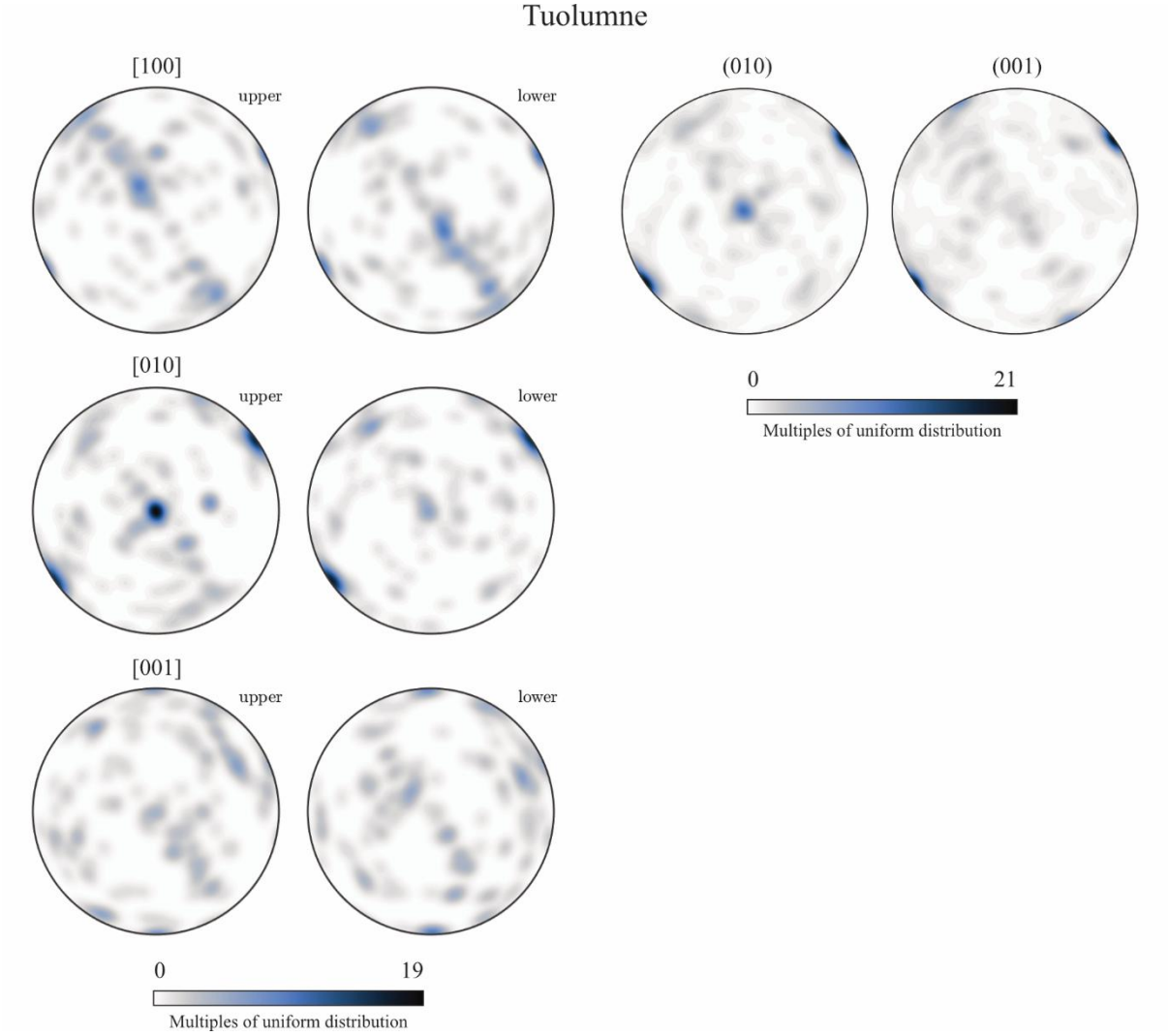


Figure 11: Pole figures of data from plagioclase inclusions in the $(\bar{2}01)_{Kfs}$ growth sectors of megacrysts from Tuolumne (n = 294) plotted in the K-feldspar reference frame (Fig. 7). No data were collected from Separation Point. We plot both hemispheres for the axes $[100]_{Pl}$, $[010]_{Pl}$ and $[001]_{Pl}$, and the lower hemisphere for poles to the $(010)_{Pl}$ and $(001)_{Pl}$ planes.

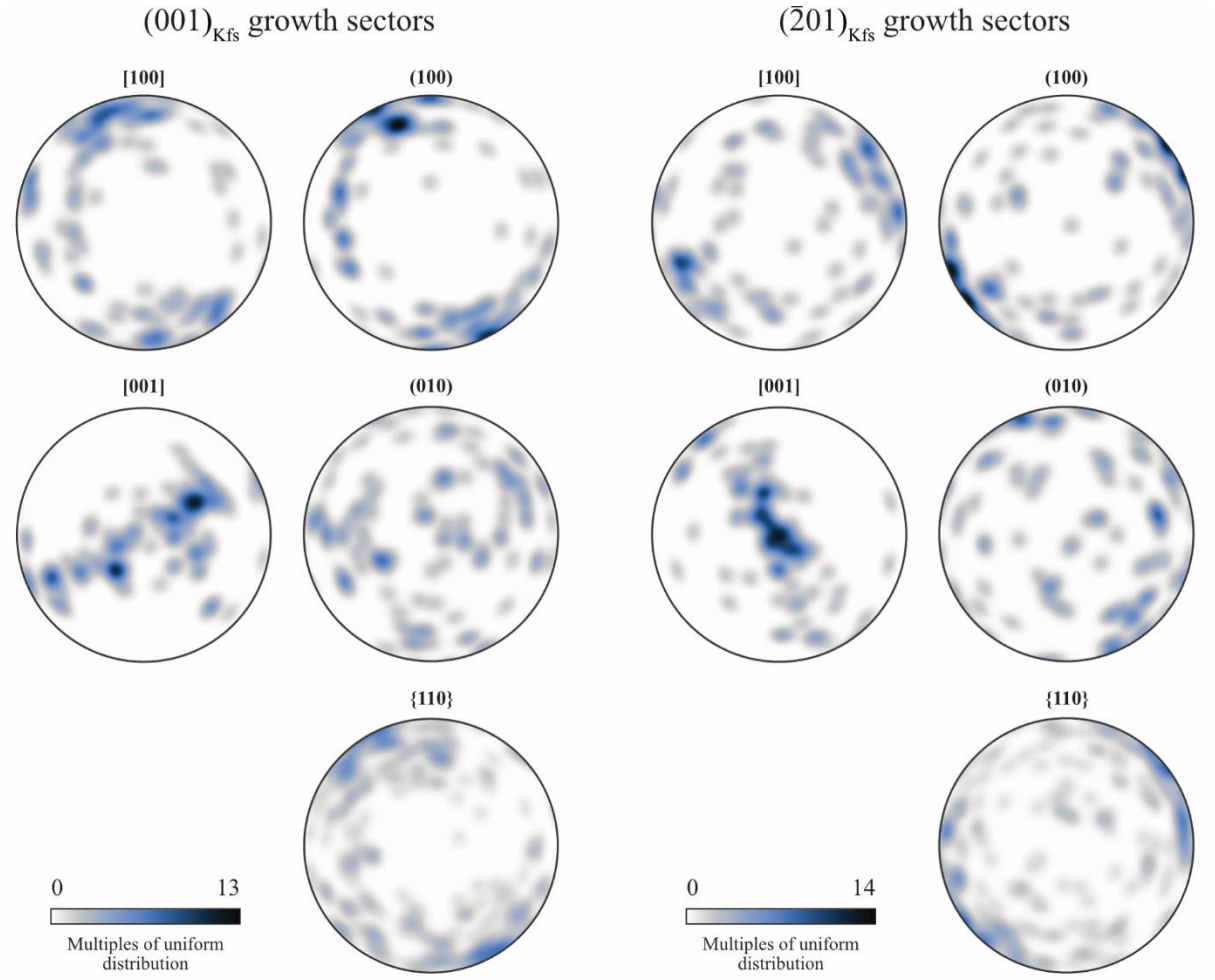


Figure 12: Lower hemisphere pole figures of amphibole inclusions in the $(001)_{Kfs}$ growth sectors (left, n = 105) and the $(\bar{2}01)_{Kfs}$ growth sectors (right, n = 90) of megacrysts from Tuolumne plotted in the K-feldspar reference frame (Fig. 7).

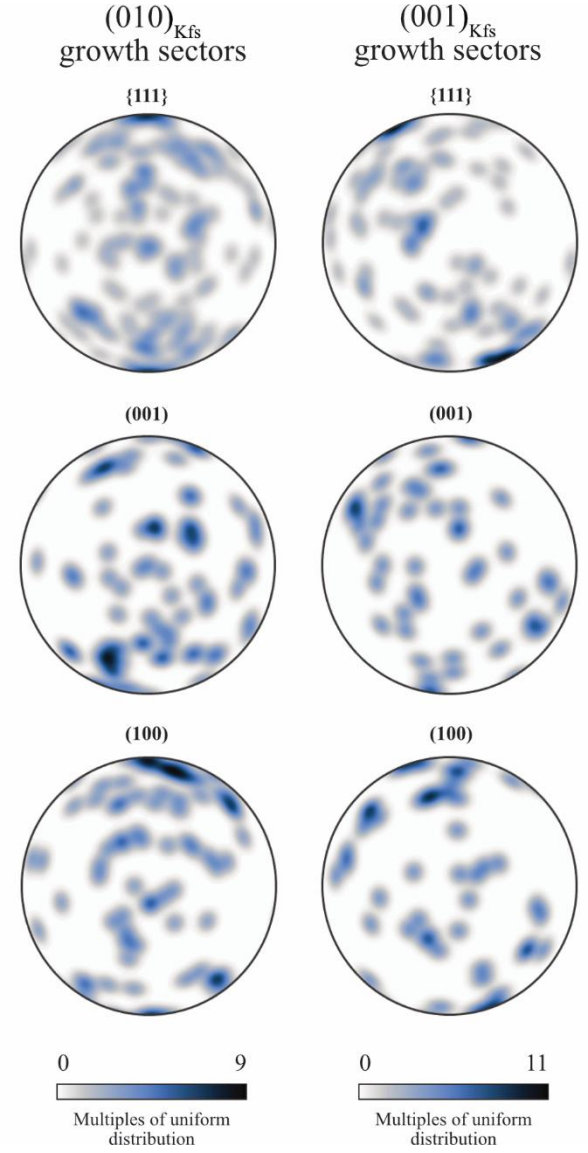


Figure 13: Lower hemisphere pole figures of titanite inclusions in the $(010)_{Kfs}$ growth sectors (left, $n = 73$) and the $(001)_{Kfs}$ growth sectors (right, $n = 49$) of megacrysts from Tuolumne and SP, plotted in the K-feldspar reference frame (Fig. 7). Titanite Miller indices are in the morphological unit cell.

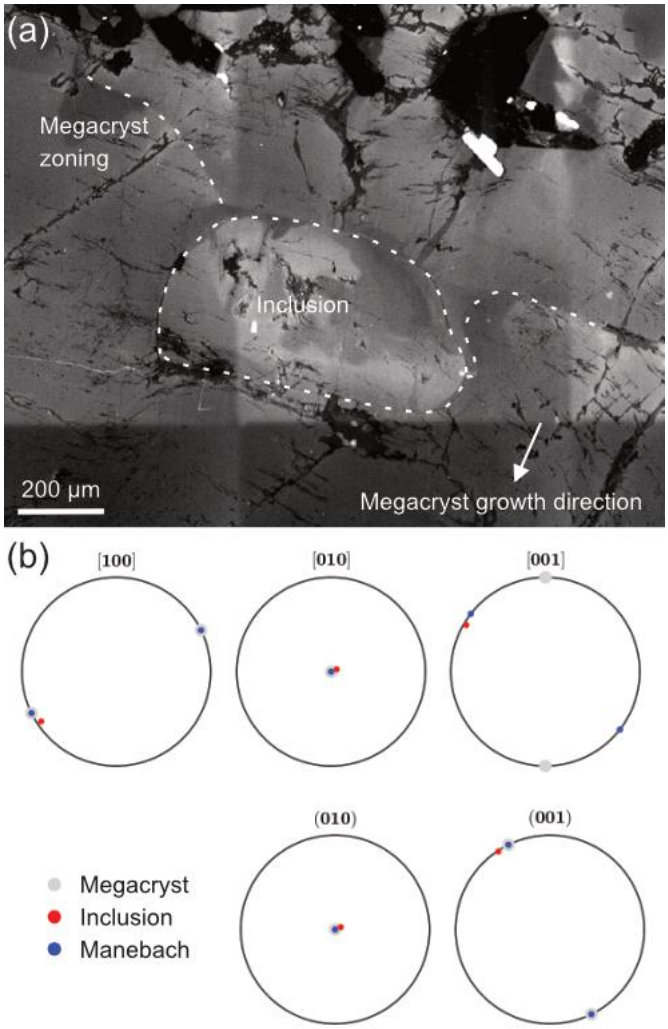


Figure 14: (a) CL map of a K-feldspar inclusion. Dashed lines indicate the megacryst compositional zoning, and the inclusion boundary. (b) Pole figures of the host crystal, inclusion, and an idealised Manebach twin (plotted in the standard reference frame, not the reference frame of the image).

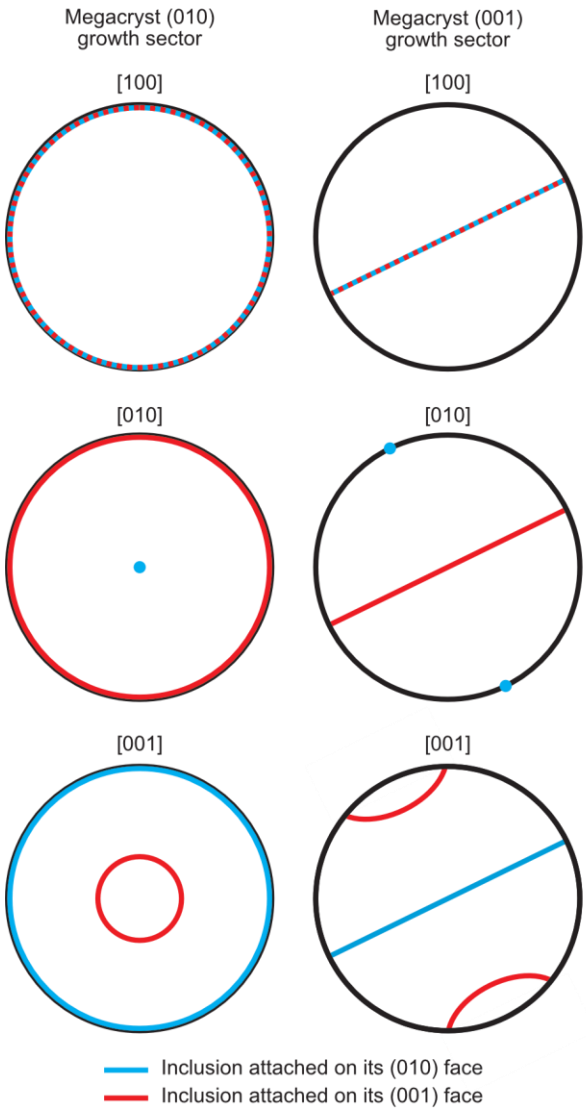


Figure 15: Modelled pole figures illustrating the expected distributions of plagioclase axes in (left) the (010) growth sectors of the megacryst and (right) the (001) growth sectors if the only controlling factor were attachment on (010) and (001).

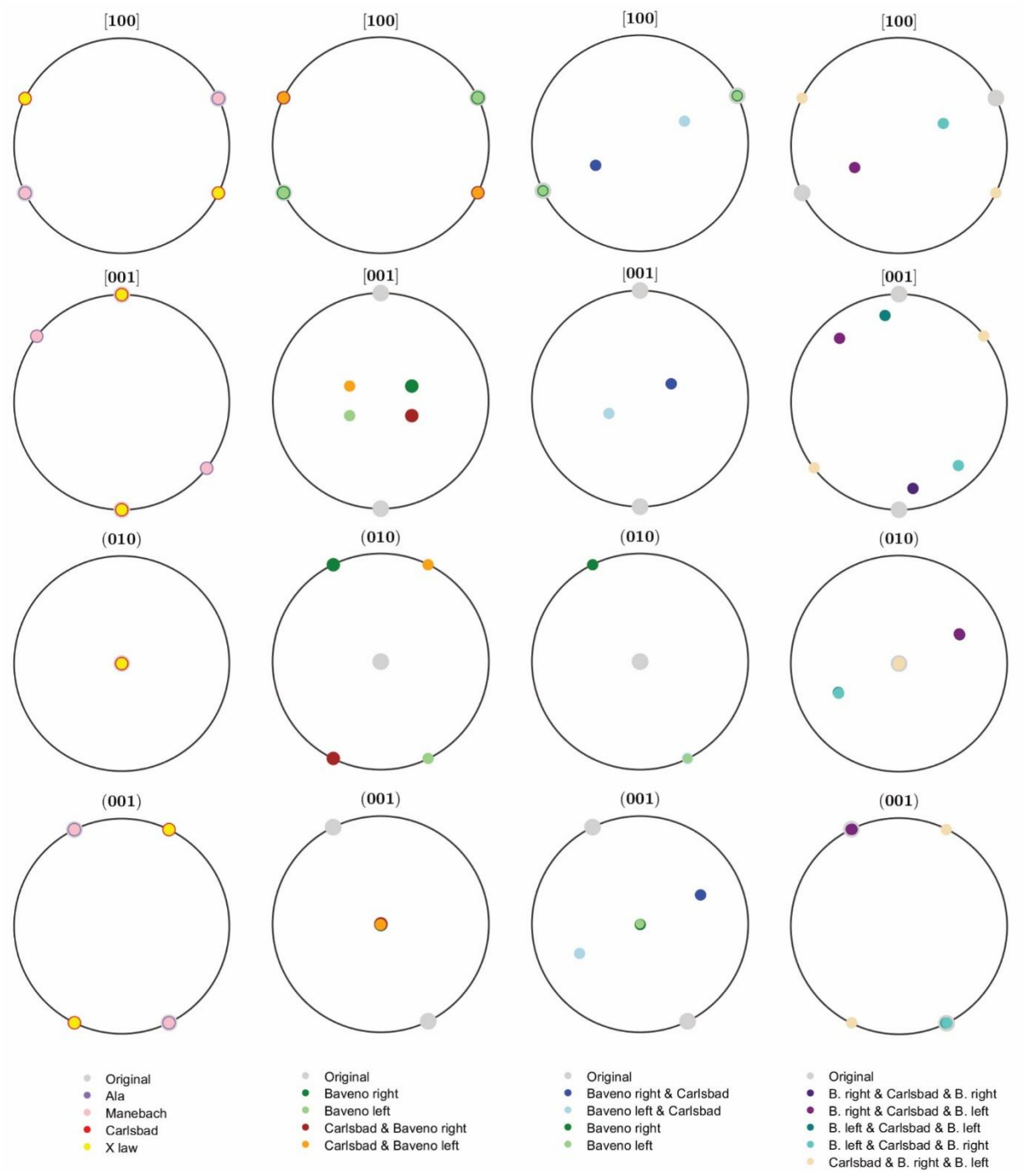


Figure 16: Modelled twin and twin combination relationships for monoclinic feldspars, relative to the megacryst reference frame (light grey) with antipodal projection onto a single hemisphere. Results are grouped into four columns to reduce overlapping of points.

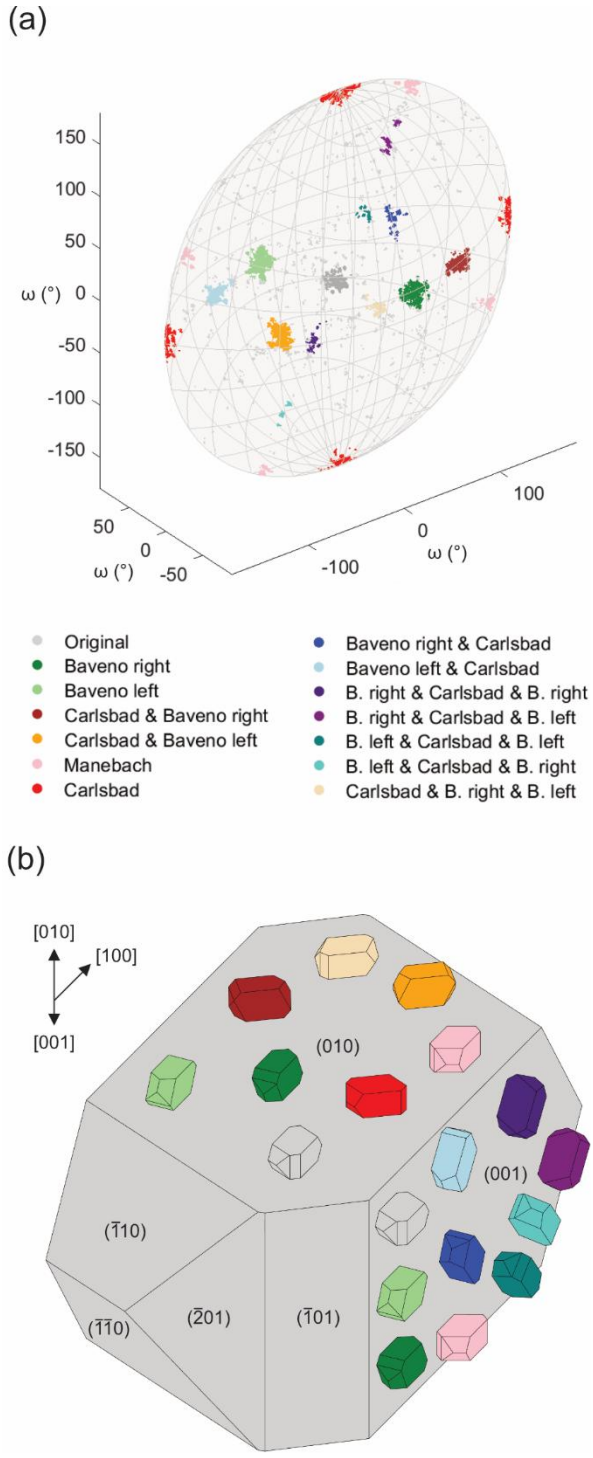


Figure 17: (a) Summary axis-angle plot showing the plagioclase inclusion data from sample SP2 coloured by orientation relationship to the host. (b) Schematic diagram of the observed synneusis relationships between K-feldspar (large) and plagioclase (small). Inclusions, coloured by synneusis relationship, are pictured on the host faces on to which they attach.