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Original paper

# Tourmaline Crystals with Corrosion Phenomena from the Skardu Area, North Pakistan
# Part 2: Inner Morphology of Tourmaline crystals with corrosion and subsequent healing

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From several hundred dark tourmaline crystals from Skardu, Pakistan, stacks of tourmaline thin sections perpendicular to the c-axis ("cross-cuts") were prepared. In contrast to standard methods, the thickness of the slices was adjusted to their optical density, as they have been ground thin until the colour zoning became visible and colour depth reached its optimum. Some of these outwardly inconspicuous tourmaline crystals show quite complex corrosion patterns in their cross-cuts. The images of the stacks of thin section deliver for each position in the crystal information about the morphology of the original crystals, the usually complex contours of the corroded crystal and the stages of growth on the way to the healed crystal. With this morphological information from the stacks of cross-cuts profiles of the crystals parallel to the c-axis were derived, which then allowed to reconstruct simplified growth histories of the tourmaline crystals.

The examples show that corrosion may take place during early, intermediate, and late stages of tourmaline growth. Some crystals exhibit even two corrosion and subsequent healing episodes. Twelve examples of such crystals are presented, illustrating the diversity and different intensity of corroded and healed tourmaline. This inner architecture of crystals is a good recorder of the discontinuous growth and dissolution history of tourmaline, giving valuable information on the sequence and intensity of supersaturated and undersaturated, corrosive fluids in the crystallizing pegmatite pocket.

*Keywords: Tourmaline Crystals, Corrosion Phenomena, Inner Morphology, Pegmatite, Skardu*
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## 1. Introduction

Tourmaline crystals, in particular dark, iron-bearing varieties, which are black in hand specimen, in many cases exhibit a wealth of information in the form of colour zones. These become visible in thin sections, when they are ground until the colour depth reaches its optimum. In many cases the final thickness is 10–15 microns only. Different kinds of colour zones have been identified (Rustemeyer 2003, 2015, 2018, 2022, 2023a):

– Each form (face type) may attract different metals and causes what is known as **sector zoning.**
– A change of the composition of the fluid surrounding the growing crystal, i.e. through consumption of certain metals or limited diffusion may result in simultaneous colour changes in all sectors, causing **concentric growth zoning**.
– Two colour domains may form simultaneously on pyramid surfaces. The mostly triangular structure in the host crystal is referred to as **a delta feature**.

The optical information provided by these colour zones illustrates which crystal forms are involved in splitting phenomena, in significant changes in crystal morphology due to supersaturation, and in healing processes after fracturing or corrosion events. The corroded tourmaline crystals presented in the first part of this paper best illustrate the process of complete healing. Internally, the healed crystals contain information about their appearance before and immediately after a corrosion event and about the way in which the crystals then continued to grow.

With a screening of the internal morphology of hundreds of tourmaline crystals from the pegmatite fields in the Skardu area in northern Pakistan over the last 25 years, more than 70 crystals were found showing internal healing patterns following corrosion. They thus contain information about the development of the miarole (pocket) area of the pegmatite where the crystals grew. Similarly to previously published studies of healed corroded tourmalines from Brazil (Rustemeyer 2003, 2015) and northeastern Bavaria in Germany (Rustemeyer and Müller 2017; Rustemeyer 2023b) the corroded crystals from Pakistan (Rustemeyer 2026) also show a wide diversity of healing forms.

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## 2. Method

### 2.1. Processing of slices

Tourmaline crystals can be easily cut with any kind of diamond saw. For precious gem-grade, wire or wafering saws are used (Reed and Mergner 1953). Crystals with many cracks should be stabilized with epoxy resin before processing. Grinding can be done on flat grinding machines with diamond discs; using graduations of 600, 1200, and 2000 (Federation of European Abrasives FEPA standard) to arrive at a thickness of about 40 micrometres. Then the final thinning is done manually on glass plates with silicon carbide powder, graduation 1200. Frequent optical control is required to achieve the optimum colour density. For final polishing, the slices are treated on a vibrating table for 24 hours with a mixture of aluminium oxide, silicon oxide, and cerium oxide.

### 2.2. Photographs

All photos of slices in this paper are taken with white backlight without any filters. Currently a digital Camera with bellows and Zeiss macro-objectives, (16, 25, 40 and 63 mm) are in use.

## 3. Examples of healing of etched tourmaline crystals from the Skardu area in Pakistan

From a collection of currently more than 70 tourmaline slice series from Skardu with internal structures of corrosion and subsequent healing 12 series were selected for this study to illustrate the diversity of the corrosion phenomena. All examples are pocket tourmaline crystals, that means that they crystallized freely in a pegmatite miarole (pocket). The set of cross-sectional slices is shown for each crystal. The slices were arranged in rows so that the slice with the smallest core area and the widest rim, i.e., the lowest section of the crystal, is at the bottom right and the highest slice is at the top left. In order to better visualize the morphology of the entire crystal, from the images of the single thin sections (Fig. 1a) a stack of slices is created in perspective view (Fig. 1b). In addition, there is a stack of strips, each cut through the centre of the crystal. This representation often allows for a good comparison of details across the different layers of the crystal and also gives a first idea of the longitudinal section of the crystal (Electronic Supplementary Material, ESM 1). With the help of the last two representations, it is then easy to reconstruct a longitudinal section of the crystal and to create a growth history of the crystal by stepwise removal of the successive growth zones that are apparent from the contrasting colours (i.e., Fig. 1d). In addition, detailed photos are used to show individual features. For a better understanding of the structures in the slices all important zones will be discussed, not only the etch and healing zones.

### 3.1. Example 1: A unilaterally heavily corroded tourmaline crystal with finely etched three-dimensional structures that grew in during recrystallization

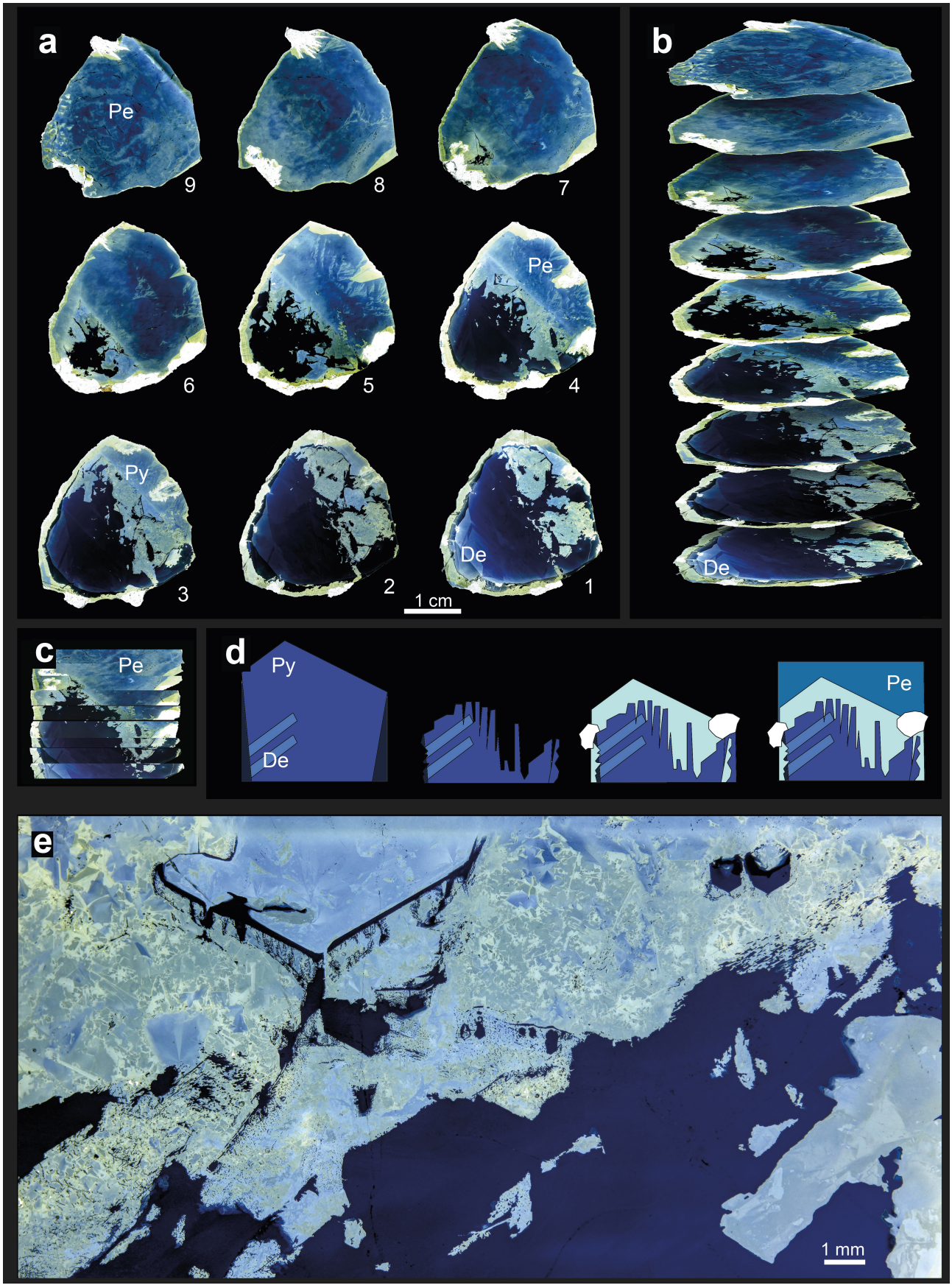
The raw crystal in the first example was a combination of the trigonal prisms a and n and the pedion c (Fig. 1 in Rustemeyer 2026). Since the lower fracture surface of the crystal ran parallel to the pedion, it had the shape of a black disc 2 cm thick, into which cleavelandite crystal tufts had grown in several places at the edges. Nine thin sections were produced from the crystal. The images in the slices (Fig. 1a), the perspective view of the slices (Fig. 1b), and the stack of centre strips laid on top of each other (ESM 1) allow the growth history of this crystal to be reconstructed and represented in a simplified diagram (Fig. 1d).

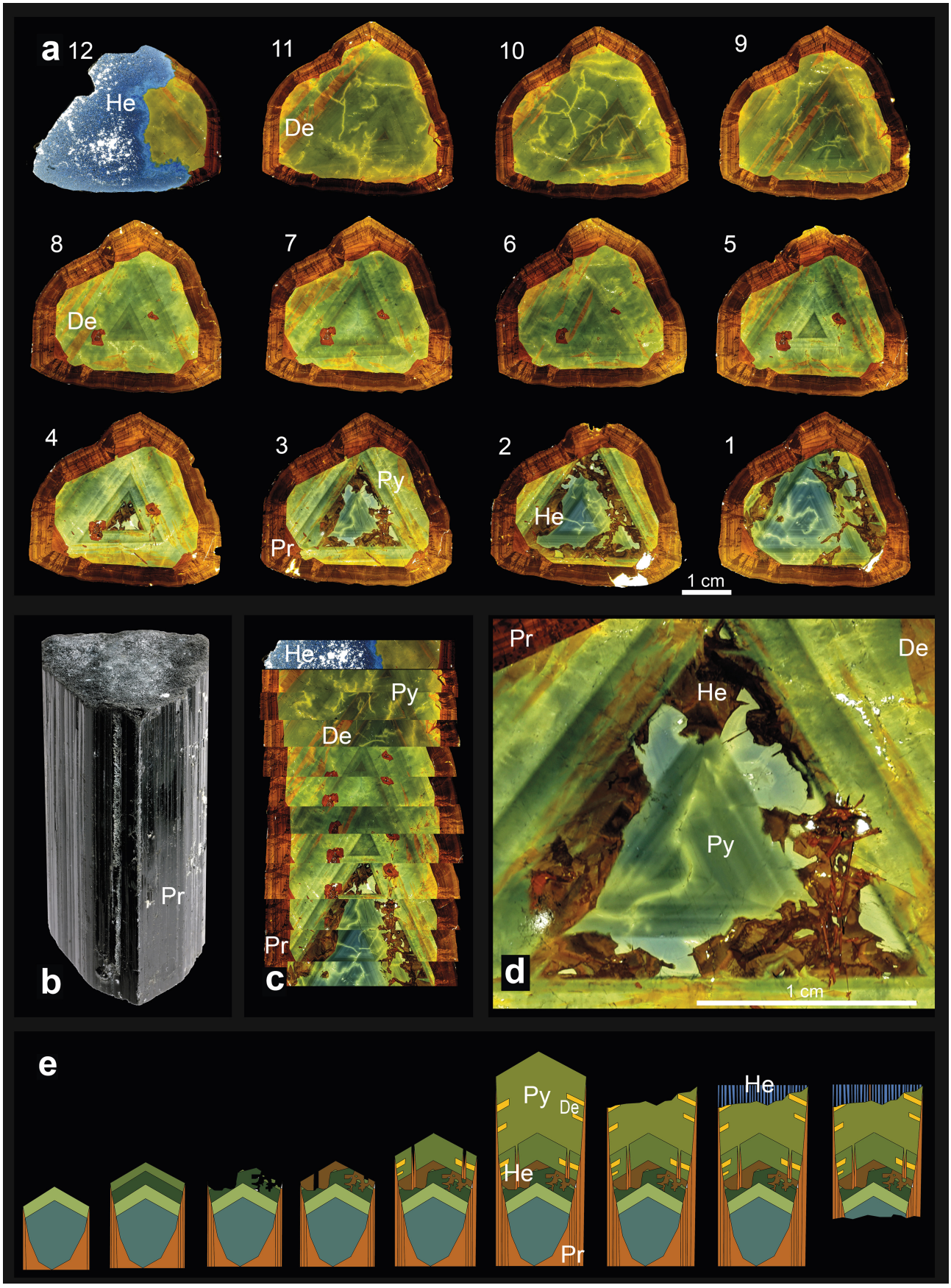
Delta features in the dark blue area show that the tourmaline crystal originally grew with a pyramidal termination (slices 1–4 in Fig. 1a). During an intense corrosion phase, fine three-dimensional structures were then etched out of this crystal on one side. Numerous thin ridges and fine columns, 10–100 micrometres thick, remained in the corroded area. In addition, the fluid corroded holes with very fine contours (Fig. 1e and ESM 1) into the compact part of the crystal that remained standing. Even bigger parts of the dark blue rim zone (the sectors of the prism faces) were etched away. The removal of the tourmaline material was significantly more advanced on one side.

In the course of healing, this three-dimensional web of light blue tourmaline was overgrown in the shape of an islands-in-the-sea structure of yellowish fine crystals as islands engulfed in grey, later upwards light blue material (Fig. 1e and ESM 1). During healing all individually starting crystals merged to form eventually a blue trigonal pyramid, which is indicated by some torn delta features (slices 5 and 6 in Fig.1a). In the final phase, a pedion face developed, giving the crystal its final shape. In the mid-stripe picture (ESM 1) colourless cleavelandite aggregates can be found, which have been partly overgrown by the tourmaline crystal. These crystals on the right side disturbed the tourmaline growth and in response it

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**Fig. 1a** – Series of crosscuts (slice ø: 30 mm, thickness 16 µm) from a Schorl crystal from Skardu, Pakistan, corroded and subsequently healed; **b** – stack of crosscuts; **c** – stack of stripes; **d** – development of the crystal; **e** – detail from the corroded and healed zone ↔ 10 mm, Inv. No. 65_07


a
Pe
9
8
7
6
5
Pe
4
Py
3
2
De
1
1 cm
b
De
c
Pe
d
Py
De
Pe
e
1 mm


a
12
He
11
De
10
9
8
De
7
6
5
4
3
Py
Pr
2
He
1
1 cm
b
Pr
c
He
Py
De
Pr
d
Pr
De
He
Py
1 cm
e
Py
De
He
Pr
He

formed a typical pyramidal yellow coloured rim feature, which became a germination point for a delta feature (marked with Pr and De on the right side of ESM 1).

The rim area of the original dark blue crystal is only about 3 mm wide in the lowest slice; this means that the uppermost part of a larger crystal is being discussed here, which was probably deeply rooted in the pegmatite rock around the miarole. Thus, the miner only cut off the part of the crystal protruding into the miarole and brought it to market.

### 3.2. Example 2: A tourmaline crystal with intermittent weak etching of the crystal pyramid

The raw crystal from Fig. 2 was a piece of crystal approximately 9 cm long and 3.5 cm wide, whose end surface resembled a pedion. More than 26 thin sections were produced from the piece. (Fig. 2a) Only 12 of these are shown in the figure, as the sections between slice 10 and 11 (Fig. 2a) were all very similar. The rim layer of the lowest crystal slice 1 is 3–6 mm wide, while that of the uppermost slice 11 is only 2 mm wide, which is why the specimen is a crystal fragment from the upper part of an initially longer tourmaline crystal. Triangular concentric growth zones with embedded delta features indicate that the crystal grew as a trigonal pyramid. The upper part of the crystal is broken off. This can be seen from the fact that the top slice 12 has a typical fracture healing structure with an irregular fracture edge of the original crystal and an overgrowth of the fracture surface with needle-shaped, oriented tourmaline crystals that touch each other laterally (ESM 2c).

During its growth history, the tourmaline initially formed a small crystal with a trigonal pyramid as its termination. At this early stage, the pyramid faces of the crystal termination were corroded with 6 mm deep holes and grooves. The holes then healed with brown tourmaline material with a complex fine structure (slices 1–4 in Figs 2a, d; ESM 2a), which arises when different sectors grow on the complex relief of differently inclined surfaces etched out of the crystal. In addition, several red-brown individually oriented needle-shaped tourmaline crystals formed; they were embedded in this brown healing zone.

The crystal then grew almost exclusively in the direction of the c-axis, *i.e.*, with almost no growth on the prism faces. This caused open tubes to form at two blocked points on the pyramid face (slices 4–8 in Fig. 2a). Only later, when prismatic growth was possible again, these tubes got filled with dark brown rim material (ESM 2b).

Finally, the tip of the crystal broke off. The fluid in the vicinity of the fracture surface, which later became supersaturated again, found numerous nucleation points there on which oriented needle-shaped blue tourmalines crystallized (slice 12 in Fig. 2a and ESM 2c). The lower fracture surface was created by a miner who knocked this healed crystal head out of the miarole.

### 3.3. Example 3: Tourmaline crystals with two corrosion and healing phases from the same pocket

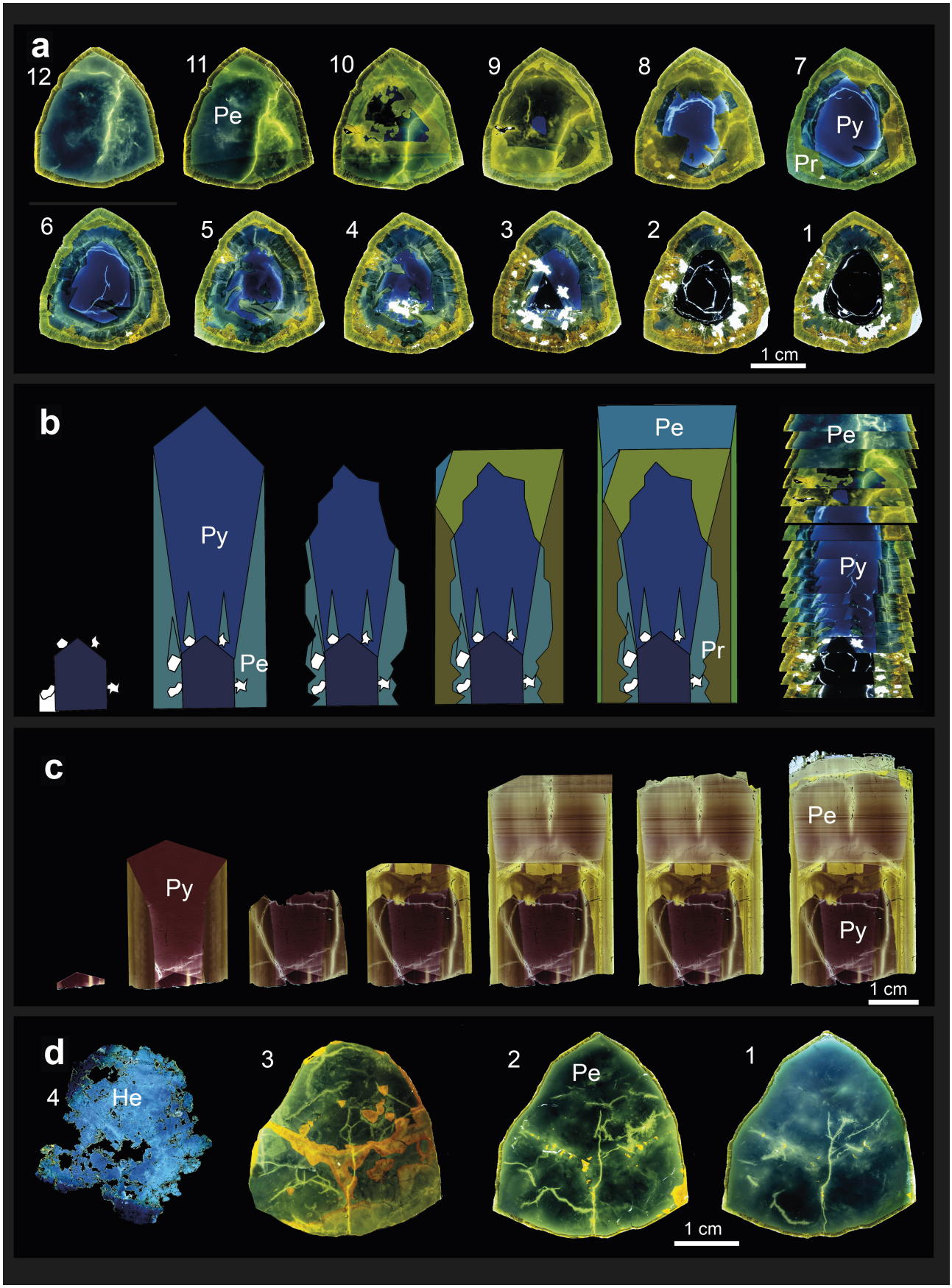
The crystal from which the thin sections in Fig. 3 a were made was similar in shape to the crystal in Fig. 2b, also with a nearly horizontal fissure as termination. Fig. 3a shows 12 sections of the crystal. Of 21 slices, 9 were omitted because there were hardly any changes between the slices in the lower row on the left and the upper row on the right. The images in the slices and the stack of cross-sectional strips reveal the following growth history (Fig. 3b): First, a small tourmaline crystal grew, with a trigonal pyramid as termination. It was then overgrown by several cleavelandite crystals. As in the previous example, the incorporated cleavelandite led to open tubes above those inclusions, as the tourmaline grew mostly in the direction of the c-axis. Later rim material crystallized laterally in the inner walls of the tubes and filled them. At an advanced stage of growth, the crystal was then intensively corroded on all faces – similar to the heavily corroded tourmaline crystals in Fig. 9 in Rustemeyer (2026).

The contours of the etched crystal are clearly visible in the pyramidal area in slice 10 (Fig. 3a): from the dark blue original crystal cross-section in the center some areas with crystallographic trigonal shapes had been dissolved. As with the etching pits, those missing parts with typical tourmaline cross-sectional shapes are oriented opposite to the outer contour of the mother crystal (ESM 3a). The images of the slices 1–6 in the bottom row of figure 3a show how severely the blue rim zones were eroded during corrosion. They were later replaced with brown tourmaline material. The detailed image ESM 3b gives an impression of how the light blue pyramidal core zone and the dark blue sector of the rim zone (Pr1 in ESM 3b) were heavily corroded from the left and bottom and later replaced by ochre coloured tourmaline material (Pr2 in ESM 3b).

The detailed photo from the top of the corroded crystal in ESM 3a shows small delta features in several places in the yellow–green healing zones; this suggests that the corroded crystal first healed with trigonal pyramidal

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**Fig. 2a** – Series of crosscuts (slice ø: 35 mm, thickness 17 µm) from a Schorl crystal from Skardu, Pakistan,corroded and subsequently healed, then broken and healed; **b** – initial crystal; **c** – stack of stripes; **d** – detail from the corroded and healed zone ↔ 10 mm; **e** – development of the crystal. (Inv. No. 66_03)


a
12
11
Pe
10
9
8
7
Py
Pr
6
5
4
3
2
1
1 cm
b
Py
Pe
Pe
Pr
Pe
Py
c
Py
Pe
Py
1 cm
d
4
He
3
2
Pe
1
1 cm

faces. Then a pedion face developed at the top, which soon spread across the entire crystal. Its colour changed from yellow–green to a shade of blue. Longitudinal cuts (parallel to the c-axis) were made through the centre of a second crystal from the same pocket. Due to the extremely strong dichroism of iron-bearing tourmaline crystals, these slices are now not olive and blue but brown, brown-violet, and ochre in colour. By gradually cutting back along the clear colour zone boundaries, the growth history of the crystal in Fig. 3c was revealed. Since the crystal comes from the same pocket, the photos resemble the graphic in Fig. 3b. A pedion face developed as a new termination on the heavily corroded tourmaline, which then continued to crystallize upward in a sequence of numerous light and dark brown coloured layers.

This zone again shows traces of a further corrosion phase in which material was removed from the crystal edges of the pedion face towards the prism faces, and etch pits and grooves formed on the pedion (Fig. 3a). The detailed image in ESM 3d illustrates with the contour of the dark brown layer (Pe1) below how deeply this pedion sector was etched. Ochreous layers filled the deepening. Subsequently numerous oscillating layers of olive-brown and brown tourmaline material created step by step again a perfect pedion face (Pe2). In three further growth spurts, a violet, a light violet, and an almost colourless layer formed. After each growth spurt, there was probably a pause during which particles could settle on the pedion face. These particles caused each a small tube parallel to the c-axis as the next layer grew (ESM 3d). Very little material grew on the prism surfaces after the first corrosion phase.

A set of thin sections was produced from a third crystal from the same pocket, the top four of which are shown in Fig. 3d; as this part of the crystal was missing from the crystal in Fig. 3a. All three crystals in Fig. 3 are traversed by white blurred irregular lines which are interpreted as healed stress cracks. It appears that dark-colouring iron has been replaced by metals that do not cause colouration in the area surrounding the cracks. The slices 2 and 3 in Fig. 3d exhibit reddish-brown filled etch pits and grooves in the matrix of the dark green coloured pedion sector. It is certainly no coincidence that the etching phenomena have spread particularly along the bleached stress and crack zones. In the detailed image (ESM 3c) those crack areas traverse even the orange healing zones of the etch pits. This is a sign that they formed only after the healing stage. The top blue slice 4 (Fig. 3d left) corresponds to the top light-coloured overgrowth layers in Fig. 3c and ESM 3d.

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**Fig. 3a** – Series of crosscuts (slice ø: 28 mm, thickness 39 µm) from a Schorl crystal from Skardu, Pakistan ,strongly corroded and subsequently healed, on top slightly corroded and again healed; **b** –stack of stripes and development of the crystal; **c** – lengthcut from another crystal from the same pocket, 27 mm wide; **d** – the uppermost slices from a third crystal from the same pocket. (Inv. No. 61_05)

### 3.4. Example 4: A tourmaline crystal with an early stage corrosion

The crystal in Fig. 4b was cut into 22 slices (Fig. 4a). The slices and the stack of central strips (Fig. 4d) reveal the growth history shown in Fig. 4c. The tourmaline crystal initially grew as a combination of a trigonal pyramid z with lateral prismatic faces. Already in an early growth phase, the pyramid surface and the prism edges towards the pyramid faces of the approximately 15 mm wide crystal were etched several millimetres deep. That can be observed in the slices 2–5 (Fig. 4a). The detailed images of slice 4 (ESM 4a and d) it can be seen that half of the dark brown rim (the sectors of the prism faces Pr) and parts the blue pyramidal core zone (Py) are missing, and the rest of this pyramidal zone is severely thinned, *i.e.*, corroded. In slice 5 above (Fig. 4a and close up in ESM 4b), the trigonal pyramidal core zone (Py) is irregularly "corroded" in all directions.

ESM 4c shows in detail the irregular etch contours. The ochreous coloured healing zone is structured, presumably due to an overgrowth on differently inclined faces of the etched crystal. Some voids indicate that the healing was incomplete. As the crystal continued to grow, the pedion face developed more and more strongly (slices 8–11), soon spreading across the entire crystal (slice 12–20 in Fig. 4a). The relative growth rate of the prism faces became smaller and smaller. After a phase of fairly calm, defect-poor crystal growth, numerous irregular bright blurred lines formed again in the following zone at the crystal top. Again, these are interpreted as stress cracks. It is striking that slice 20, the third from the top is almost perfectly formed without these bright stripes. In the uppermost slices 21 and 22 the tourmaline crystal is subdivided into numerous parallel blue crystals. Noteworthy, slice 20 in Fig. 4a (close up in ESM4d) exhibits a fine white net structure, which was already described and discussed on other crystals in Rustemeyer (2026).

### 3.5. Example 5: A heavily corroded crystal with an oscillatory recrystallization zone

The crystal, of which only the upper part is visible in Fig. 5e, was processed into a series of 24 thin sections (9 of which are shown in Fig. 5a). From the images of the thin sections, the perspective stack of slices (Fig. 5b), and the central strip set (Fig. 5c), the growth history of the crystal could be reconstructed in Fig. 5d. The crystal initially grew as a combination of a trigonal pyramid with a series of prismatic faces. In the core zone, a sequence of coloured trigonal pyramids crystallized, ranging from

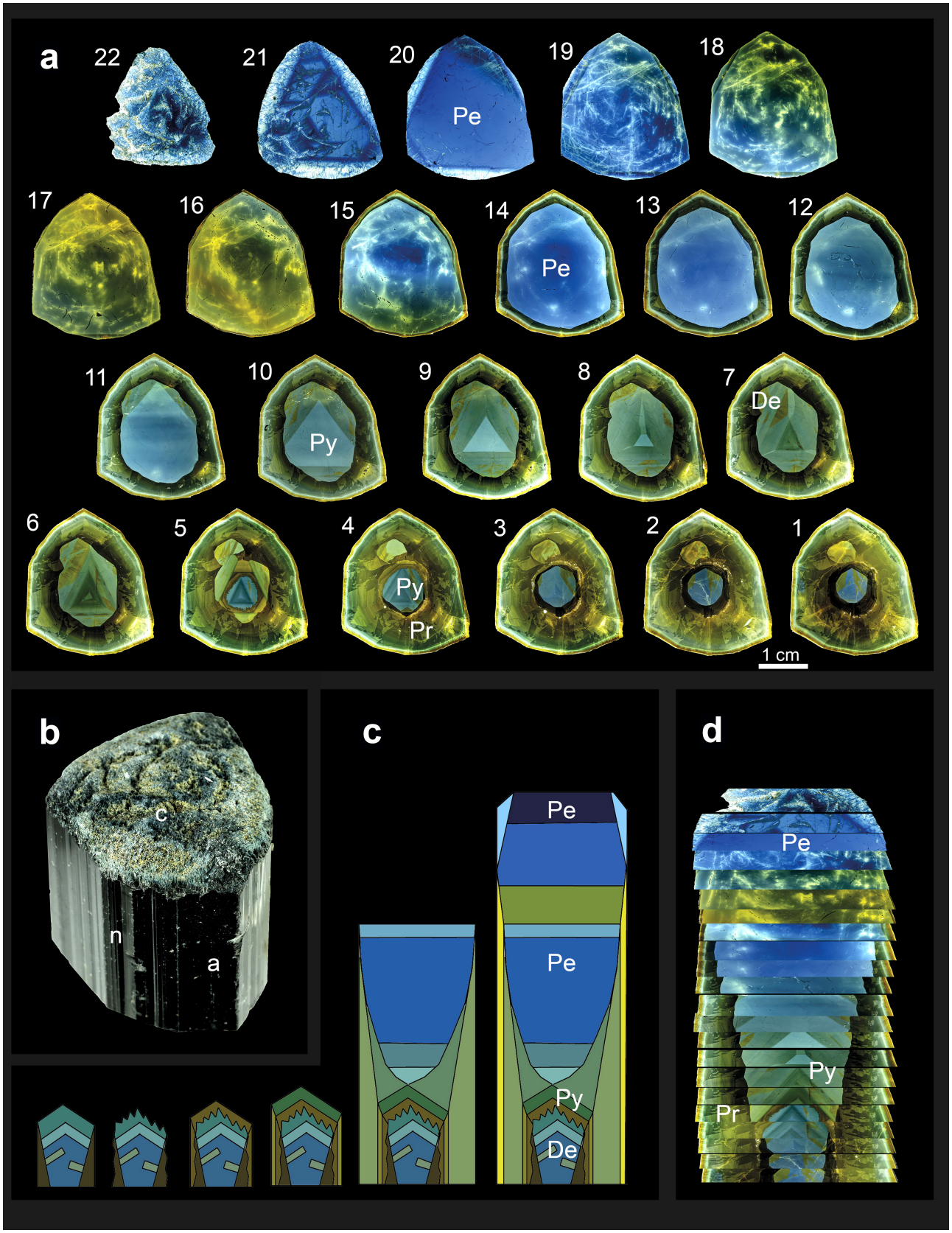



**Fig. 4a** – Series of crosscuts (slice ø: 37 mm, thickness 30–400 µm) from a Schorl crystal from Skardu, Pakistan,corroded and subsequently healed; **b** – initial crystal; **c** – development of the crystal; **d** – stack of stripes. (Inv. No. 66_07)

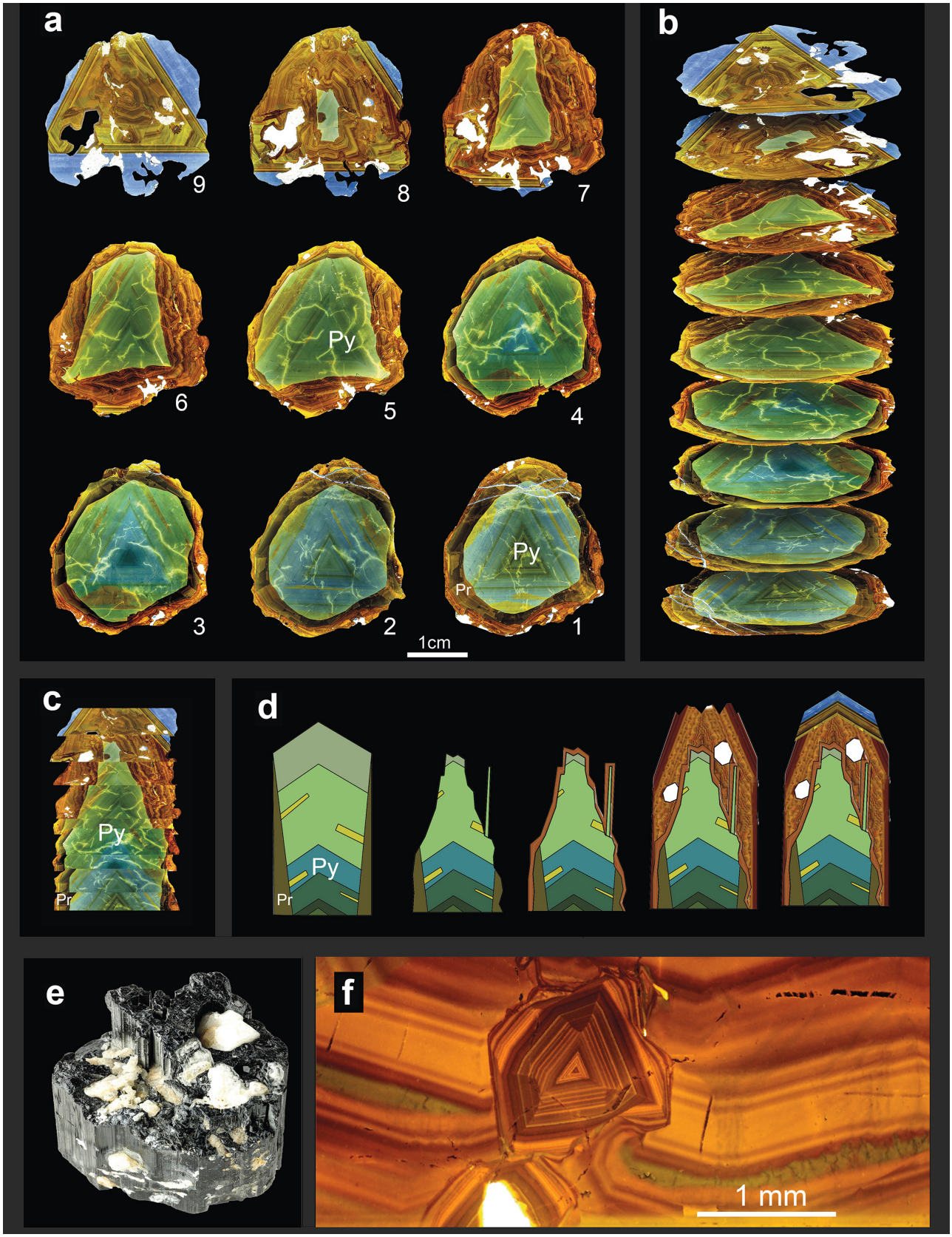
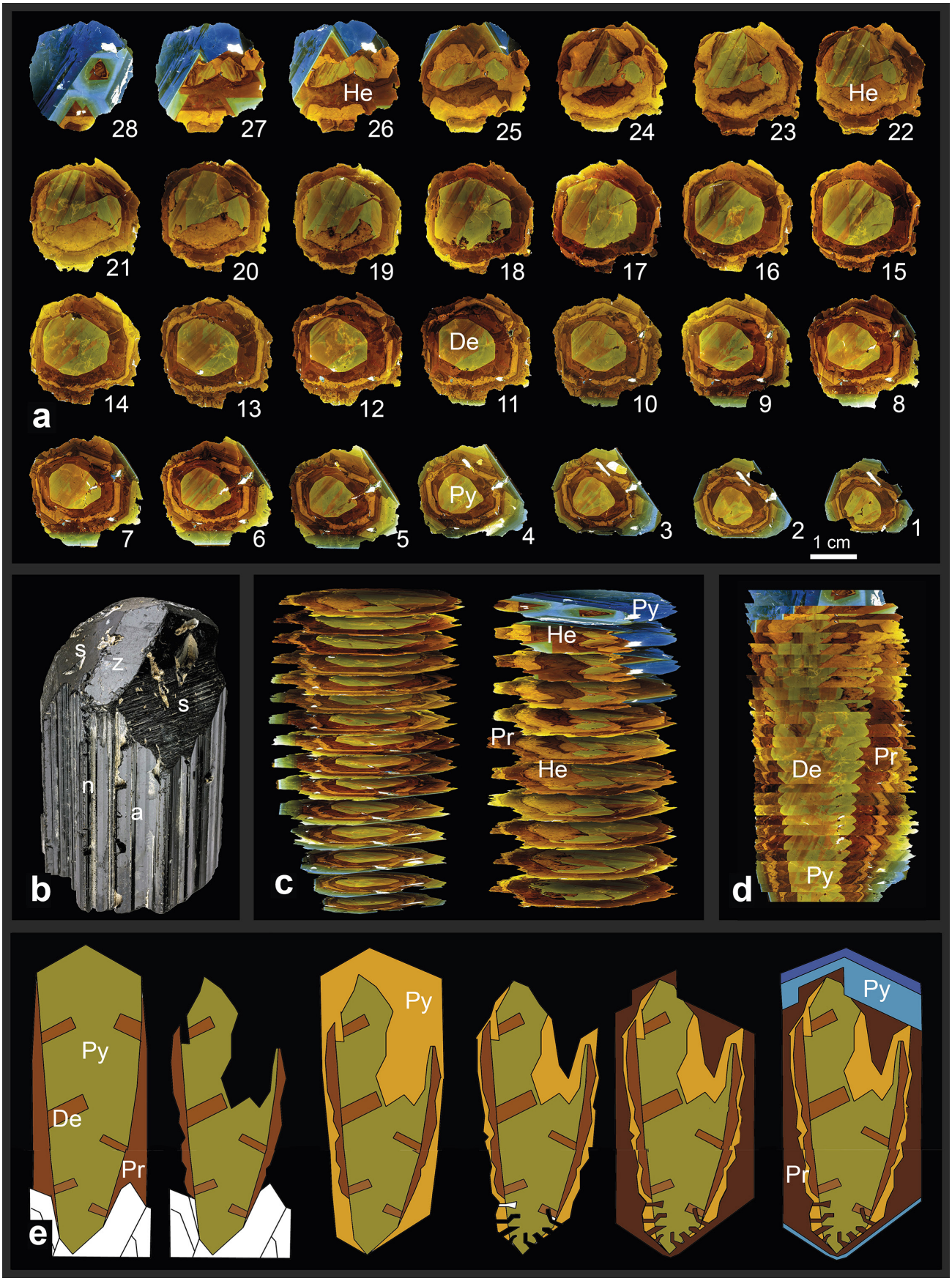



**Fig. 5a** – Series of crosscuts (slice Ø: 32 mm, thickness 16 µm) from a Schorl crystal from Sardu, Pakistan, corroded and subsequently healed; **b** – stack of the crosscuts in perspective view; **c** – stack of stripes; **d** – development of the crystal; **e** – initial crystal; **f** – second to last slice with the borders of etching. (Inv. No. 64_11)


28
27
He
26
25
24
23
He
22
21
20
19
18
17
16
15
14
13
12
De
11
10
9
8
a
7
6
5
Py
4
3
2
1
1 cm
b
s
z
s
n
a
c
Py
He
Pr
He
d
De
Pr
Py
e
Py
De
Pr
Py
Py
Pr

dark blue to olive to green. Brownish delta features also formed within these faces.

In the next step, the upper part of this crystal was so heavily corroded that only a stump and a slim column remained. Subsequent healing process took place in a unique manner, with a complex combination of trigonal and ditrigonal pyramids in which light brown and dark brown layers formed an oscillating pattern. This resulted in a concentric pattern similar to agate, which is very unusual for healing zones in tourmaline crystals. Some cleavelandite tufts grew within the healing zone and form the white areas in the slices 6–9 in Fig. 5a and ESM 5a. ESM 5a–c gives a detailed impression of the complex healing zone He1 around the greenish remains of the corroded core area. At the bottom of ESM 5c, which is a detail from slice 9 (Fig. 5a), a borderline between the healing sector HE1 with mainly ditrigonal pyramids and the healing sector He2 of a trigonal pyramid is shown. Contours of the ditrigonal pyramid t and the trigonal pyramid z should provide orientation.

The complexity of the patterns in healing zone 1 arises from the superposition of three effects: First, during crystallization, significant irregularities in the corroded core and a large deviation from the ideal crystal form had to be compensated for. Second, the transition from a complex crystal form with a combination of ditrigonal and trigonal pyramids to a simple trigonal pyramid took place. Third, there were additional inclusions of randomly grown tourmaline and cleavelandite crystals, which were also overgrown in layers and integrated into the healing sectors (Fig. 5f) This cross section of a single tourmaline crystal illustrates the combination of trigonal and a ditrigonal pyramid.

### *3.6. Example 6: A tourmaline crystal that was twice heavily corroded in the final growth phase with several healing zones*

The specimen shown in Fig. 6b has a fractured surface at the bottom, which was sawn off for an initial test cut – as slice 28 in Fig. 6a. The crystal was then processed into 29 thin sections (slices 1–28 in Fig. 6a and the lowest slice in ESM 6b). The rim zone in the slices became wider and wider – this is an unmistakable sign that one is moving downwards in the crystal. The beautifully crystallized termination of the crystal is therefore actually its lower part, which was broken off and subsequently healed. In Fig. 6a, the slices were arranged in rows so that the slice with the smallest core area, i.e., the lowest slice 1 of the crystal, is at the bottom right and the highest section 28 is at the top left. In the bottom part (slices 1–17), the tourmaline crystal shows the classic division between the core area consisting of the olive-coloured sectors of the pyramid faces (Py) with scattered brown delta structures and the brown rim area consisting of the sectors of the prism faces (Pr). In slices 18–28, a remarkable development of very complex healing zones was discovered. And another one in the lowest slice displayed in ESM 6b.

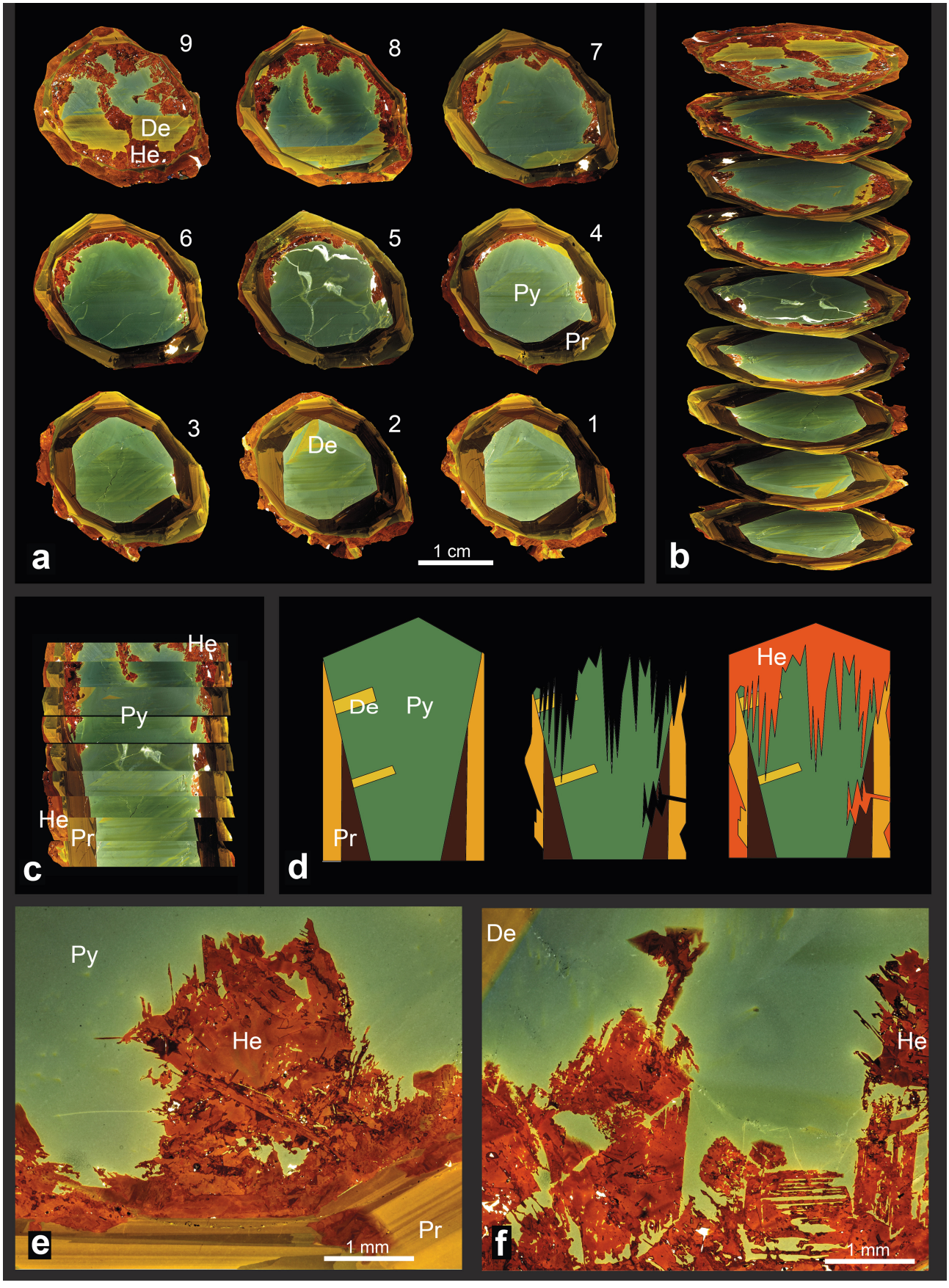
The growth phases of this crystal were reconstructed (Fig 6e) from the images of the slices, the perspective view of the slices, and the assembled middle cross-section strips (Fig. 6c). Initially, the tourmaline crystal grew in a conical shape. This is because, in the early stages of its growth, it had to share space with other adjacent cotectic minerals. If the tourmaline crystal has enough space to grow completely freely, the parallel prismatic surfaces crystallize along the entire outer surface of the crystal, so that the columnar crystal has the same width on each level. As mentioned above, the crystal tip is surprisingly a broken off conical lower part, which, in the course of the tourmaline's development, healed with olive-coloured and finally blue material to form a combination of two steep trigonal pyramids (Fig. 6b). The slices 1–5 resulted from slicing this pyramid. Without any competing neighbours, the tourmaline crystal continued to grow in the shape of a trigonal olive-coloured pyramid with some embedded brownish delta features. The dark brown prism faces crystallized with lower rates on the sides.

In a late phase of growth, there was a strong corrosive attack on all faces of the crystal, especially strong on its antilogous terminations, which are oriented upwards in the graphic (Fig. 6e). At the analogous pole (ESM 6b), the corrosion etched holes into the pyramid faces. In addition, the brown rim area (prismatic sector) in the lower part of the slice was dissolved by the fluid. The entire, now heavily corroded crystal probably looked similar to the heavily corroded tourmaline crystals with large holes in their core area in the photos in the first part of the paper (see Fig. 8 in Rustemeyer 2026).

During the subsequent healing process, an ochre-coloured tourmaline layer He1 (ESM 6a) grew around the bizarrely shaped corroded crystal (Fig. 6e). In a second phase of corrosion, this ochre-coloured layer was partially removed and again a hole was dissolved into the pyramidal part. In addition, deep holes were etched into the base of the crystal, so it must be assumed that the crystal had broken off before this phase. This step was followed by another healing period with brown material (He2). Finally, the crystal was overgrown by green and blue material. Close up from the penultimate slice 27 (Fig. 6a) is shown in ESM 5a, displaying green zones of the original crystal (Py) with brown delta features (De) in the centre, the ochre-coloured first healing zone (He1), the brown second healing zone (He2) followed

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**Fig. 6a** – Series of crosscuts (slice ø: 26 mm, thickness 19 µm) from a Schorl crystal from Skardu, Pakistan, twice corroded and subsequently healed; **b** – initial crystal; **c** – stack of the crosscuts in perspective view; **d** – stack of stripes; **e** – development of the crystal (Inv. No. 63_10)


9
De
He
8
7
6
5
4
Py
Pr
3
2
De
1
1 cm
a
b
He
Py
He
Pr
c
De
Py
Pr
He
d
Py
He
Pr
1 mm
e
De
He
1 mm
f

by a series of overgrown small green, brown and finally large blue areas (Py2). The same sequence of colours can be observed in the lowest slice (ESM 5b). In addition, it contains the typical pattern of hole etching and subsequent healing in its core area.

### 3.7. Example 7: A tourmaline crystal corroded with deep, narrow holes at its top and then healed

The original crystal from the series of slices in Fig. 7 grew as a combination of a trigonal pyramid z and a series of prismatic faces (Fig. 1 in Rustemeyer 2026). The sectors of the pyramid faces (Py in Fig. 7) are green with a few embedded ochre-coloured delta features (De), while the sectors of the prismatic faces (Pr) are dark brown on the inside and then ochre-coloured layer on the outside. During a phase of severe corrosion, deep cavities parallel to the c-axis were dissolved into the terminations, concentrated at the border of the core area. The sectors of the prismatic faces were etched with less intensity from the outside. What is remarkable is the fineness of the cavities in the original crystal and the fineness of the columns of the original crystal that remained in the etched areas (Figs. 7e, f).

The heavily corroded crystal was filled by reddish-brown tourmaline material. In these healing zones, there are dark brown spots in many places with partially straight boundaries (Figs. 7e, f). These could be columnar crystals that were later embedded in a homogeneous tourmaline matrix. Even in the finest channels, only very few parts remained unfilled – crystallization during healing was nearly perfect. This type of tourmaline crystal, deeply corroded with narrow, healed cavities is very common in the Skardu area, Pakistan.

### 3.8. Example 8: A Tourmaline crystal that corroded twice with deep holes in its terminations and then healed.

At first glance, the images of the tourmaline slices 1–8 of the crystal shown in ESM 7a look very similar to the Example 7 discussed above, but in detail this case is more complex. Two parallel crystals grew in their core area as trigonal pyramids z (Py) with numerous embedded delta features (De). Normal crystallization was interrupted with a period with higher oversaturation and the beginning of skeletal growth. Slices 3–5 exhibit a typical pattern with irregular elongated holes open in the centre of a pyramid face (Rustemeyer 2022). ESM 8a shows this phenomenon in the detailed image from slice 5 in ESM 7a with 4 cavities, one of which remained as void in the crystal. In the others cavities, rim material crystallized as dark brown layer on the inner prism faces of the cavities, and from the ground numerous light brown tourmaline grew and filled the cavities. Delta features grew from the edges of these holes into the pyramid faces.

The ratio of rim thickness to core diameter suggests the specimen was the middle section of a longer crystal. After the tip of the crystal broke off, the fracture surface became severely corroded, resulting in deep holes which healed later. Enlarged images of the healing zones (ESM 8b–d) reveal a fine brown network. As in the previous example, the colour pattern of the blue pyramid sectors and the ochre-coloured delta structures are clearly visible as island-in-the-sea structure within the brown web of the healing zones. In addition, there are numerous inclusions, often zoned in green, blue, and brown, many of which exhibit a typical sawtooth-like contour. These inclusions can be distinctly distinguished from the background pattern of the initial crystal. These findings can be interpreted as two successive periods of corrosion and healing (ESM 7b): A first corrosion step with etched out holes in the fractured termination of the tourmaline crystal was followed by a healing with green, blue, and brown zoned tourmaline material. Then, in an apparently more intense second corrosion step, a deep, net-like structure was dissolved from the original crystal and the already existing healing zone. The most resistant parts of the first healing zone remained in the form of dissolution bodies – the etched surfaces thus form the typical sawtooth-like patterns in the cross-section.

In some areas of the brown healing zone, there are dark stripes oriented in a trigonal pattern (ESM 8d); these indicate larger single-crystal regions where the crystal in the healing zone had two trigonal pyramids as terminal faces. In other places, concentric brown structures can be observed. Each has a yellow dot at its centre. These were fine needle-like columns that remained after the corrosion of the original crystal and were encased concentrically during healing.

### 3.9. Example 9: A tourmaline crystal with extremely narrow and deep hole etching and subsequent healing

The tourmaline crystal of the slice series in Fig. 8 has grown homogeneously in the shape of a trigonal pyramid z. The schorl crystal was processed into the slices 1–11 in Fig. 8a. Parts of a single large delta feature, which is arranged in the crystal like an inclined piece of pie, can be

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**Fig. 7a** – Series of crosscuts (slice ø: 25 mm, thickness 15 µm) from a Schorl crystal from Skardu, Pakistan, corroded and subsequently healed; **b** – stack of the crosscuts in perspective view; **c** – stack of stripes; **d** – development of the crystal; **e, f** – details from the etched and subsequently healed zone. (Inv. No. 55_20)

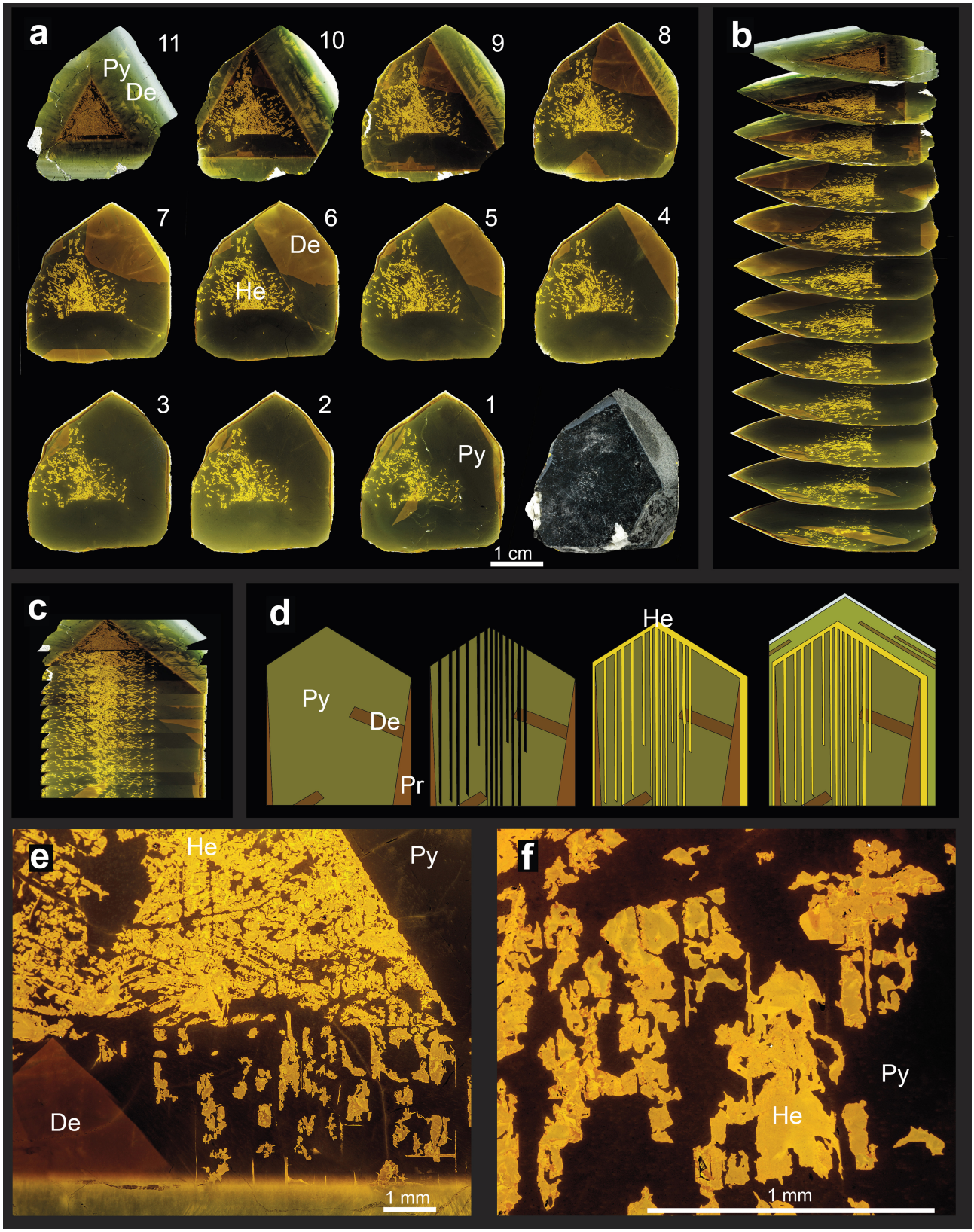



**Fig. 8a** – Series of crosscuts (slice ø: 35 mm, thickness 15 µm) and view on the top of a Schorl crystal from Skardu, Pakistan, corroded with deep narrow cavities and subsequently healed; **b** – stack of slices in perspective view; **c** – stack of stripes; **d** – development stages of the crystal; **e, f** – details from the etched and subsequently healed zone. Sectors: Py trigonal pyramid, Pr prism faces, Pe pedion face c, De delta feature, He healing zone. (Inv. No. 65_05)

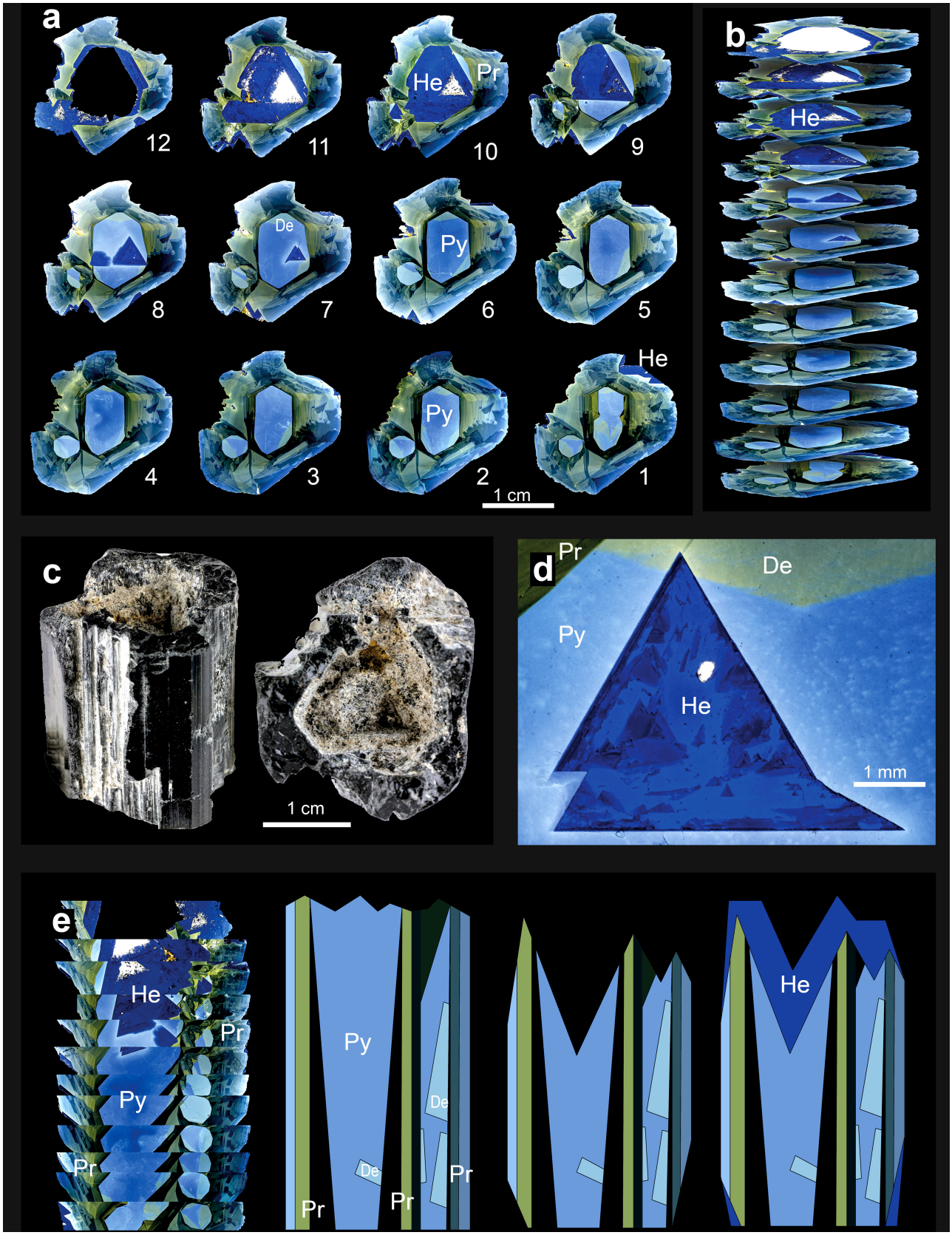
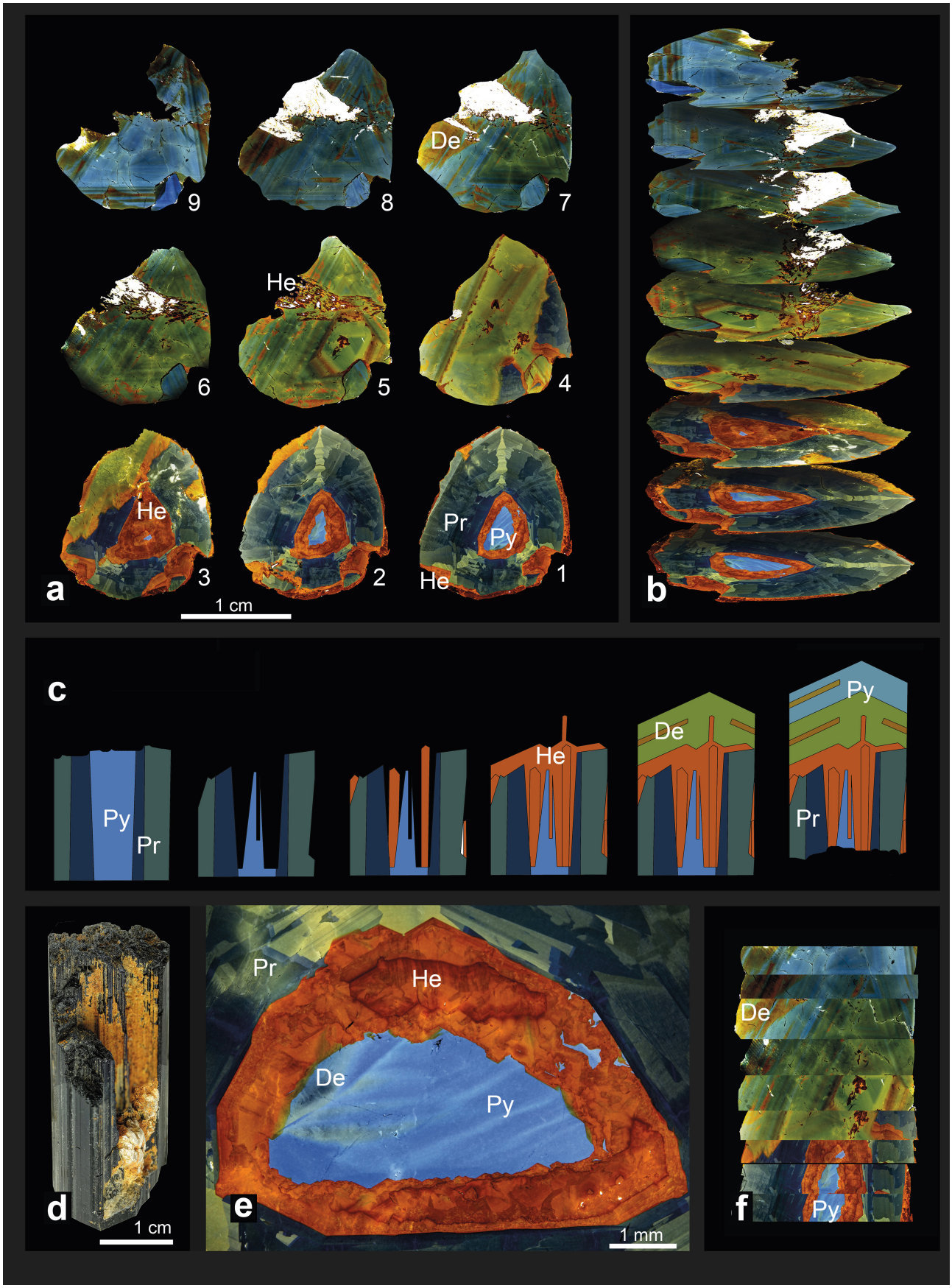



**Fig 9a** – Series of crosscuts (slice Ø: 22 mm, thickness 11 µm) from a Schorl crystal from Skardu, corroded core and subsequently partially healed; **b** – stack of slices; **c** – initial crystal, side view and top view; **d** – close-up from the healed area in the core zone of slice 7; **e** – stack of stripes and development stages of the crystal. Sectors: Py trigonal pyramid, Pr prism faces, Pe pedion face c, De delta feature, He healing zone. (Inv. No. 58_50)


9
8
De
7
6
He
5
4
He
3
2
Pr
Py
He
1
a
1 cm
b
c
Py
Pr
He
De
Py
Pr
d
1 cm
Pr
He
De
Py
e
1 mm
De
Py
f

seen in the slices 4–9. During a phase of extreme pitting corrosion, narrow cavities up to 4 cm deep formed vertically in the pyramidal area, *i.e.*, parallel to the c-axis of the crystal. The crystal then healed with ochre-coloured tourmaline substance. The extremely delicate cavity structure is shown in the enlarged image in Figures 8e and f along the contours of the orange-coloured areas. Remarkably, extremely fine pillars and columns and walls from the original crystal measuring around 0.1 mm in diameter remained standing in the corroded area at the end of etching. In the detailed images in Figs 8e and f, they are completely filled with ochre-coloured healing substance. Again, it is astonishing that no free spaces remained when the very fine channels were filled, when tourmaline started to crystallize again. The uppermost slices 8–11 show that the ochre-coloured healing layer grew thinly on the trigonal pyramid, which then continued to grow with green tourmaline material. Finally, a thin light blue layer formed.

### 3.10. Example 10: A Tourmaline crystal with a hole structure in the core area, which only partially healed

The crystal in Fig. 9c looks like a tourmaline crystal with a corroded core area. When the crystal was processed into a set of 12 slices (Fig. 9a), it surprisingly turned out that in this case, a more severe cavity corrosion had already partially healed. The surface ratio of the core zone to the rim zone indicates that the crystal was the broken off lower part of a much longer tourmaline crystal. During a corrosion phase, the core area was deeply corroded, while only a few saw tooth-like structures were dissolved from the outer rim area. In this crystal the rim zone is strongly sector-zoned. ESM 9 exhibits details from the rim zone. Labels depicting prismatic cross-sections were added to the image. The yellow ones refer to the new outer surface created by corrosion. It can be seen that a sawtooth-like structure is created because the tourmaline crystal retreats to the surfaces of the trigonal prism m and the hexagonal prism a during corrosion. Several detached trigonal prisms m then form the saw teeth. The white cross-sections of prism surfaces (a, n and dx in ESM 9) refer to the specific prism sectors in this rim area. In the centre is the yellowish-green trigonal pyramid, which provides crystallographic orientation in many tourmaline slices. In this sector, isolated stripes of the ditrigonal prism dx can also be found. The very dark sectors could not be precisely indexed; this is only possible if a narrow band with a colour change runs through these sectors. In some other equivalent crystals, it was identified as another ditrigonal pyramid (Rustemeyer 2022). The strongly corroded crystal healed with marine blue material. Darker single crystals formed fist on the etched surface; they were later embedded in a blue matrix (Fig. 9d). During crystallization, the bottom of the deep hole in the core area of the crystal was filled almost completely. On the outer side, the blue tourmaline material also crystallized mainly in the sawtooth gaps previously etched into the crystal.

⇦

**Fig. 10a –** Series of crosscuts (slice Ø: 15 mm, thickness 20 µm) from a Schorl crystal from Skardu, broken, then corroded in the core zone and subsequently healed; **b –** stack of slices; **c –** development stages of the crystal, side view and top view; **d –** initial crystal; **e –** detailed picture from the core area and the healed zone rim zone from the bottom slice; **f –** stack of stripes. Sectors: Py trigonal pyramid, Pr prism faces, Pe pedion face c, De delta feature, He healing zone. (Inv. No. 58_51)

### 3.11. Example 11: A tourmaline crystal with a healed tube-shaped corrosion zone between its prismatic rim zone and pyramidal core zone

The schorl crystal in Fig. 10d exhibited no clear terminations. It was broken at the bottom where it had the full cross-section of a single tourmaline crystal. Towards the top it was overgrown with cleavelandite on one side, which blocked further growth in this area of its termination. This is an indicator that the tourmaline growth at this stage was only possible in the direction of its c-axis (Fig. 1), as often observed in the end phase of tourmaline growth. The crystal was not able to spread sideways over the grown cleavelandite tufts. Towards the top, the crystal split up into numerous trigonally oriented lamellae (parallel to the c axis and oriented along the a1, a2 and a3-axes in Fig. 1). Such a subdivision was observed in numerous crystals from Skardu. Sixteen thin sections were prepared from the crystal. The bottom nine sections are shown in Fig. 10a; the aforementioned subdivision zone at the top has been omitted. In the bottom four slices 1–4, the remains of a tourmaline crystal with a small light blue pyramidal core zone and a broad dark blue, strongly sector-zoned rim can be seen. Towards the top, this rim area shows a typical irregular fracture structure. Thus, these four slices contain a fragment from the lower part of an originally longer crystal – this stump also marks the beginning of the growth history in Fig. 10c.

After a fracture event the broken crystal was deeply corroded along the boundary between its core and rim area. In addition, some parts of the outer prism faces were dissolved. Later the etched relief of the corroded crystal was overgrown inside and outside with reddish-brown tourmaline material, forming the conspicuous tube-shaped zone around the core area. In detail, Fig. 10e shows that narrow columns of material from the core zone remained within the healing area after etching. The entire reddish-brown area is structured. In some areas

they exhibit colour pattern bearing a strong resemblance to the surfaces of heavily etched tourmaline crystals. ESM 10a shows a pattern of seemingly stacked isosceles triangles; it could have been created by overgrowth on the typical etch relief of stacked pyramidal etch pits and etch hillocks shown in ESM 10b. Similarly, the zigzag patterns in ESM 10c are interpreted as an overgrowth on the etched terraced landscapes of the pyramid z shown in ESM 10d. In addition, ESM 10c shows a single cross-section of a ditrigonal pyramid; this shape occurred at least temporarily during healing. A few thin, needle shaped individual red brown crystals have grown on the red brown healing layer. They can be discovered as smaller dots in the later overgrown green pyramidal layers, which also contain brown delta features (slices 4–6 in Fig. 10a). In the last stages of growth, the crystal has been disturbed with the already mentioned overgrowth of cleavelandite, but continued to crystallize fist as green, then as blue pyramid (Fig. 10c).

### *3.12. Example 12: A corroded and incompletely healed tourmaline crystal with numerous cavities*

The crystal, from which the 13 slices shown in ESM 11a were made, had the shape of a steep truncated cone, 6 cm high and 4 cm wide at the base, with a very irregular outer surface. The perspective view of the slices (ESM 11b), and the stack of centre strips laid on top of each other (ESM 11c) allow the growth history of this crystal to be reconstructed and represented in a simplified diagram (ESM 11d). The teal-coloured core area of the crystal with the sectors of the pyramid faces is 5 mm narrow in the lowest slice 1 (ESM 11a) and increases to 20 mm in the upper slices 11 and 12. Thus the specimen was the broken off lower part of a much larger crystal. The rim area is divided into three concentric zones, with the colours changing from olive green to dark brown to ochre from the inside to the outside (ESM 11e, f).

During a phase of corrosion, the aggressive fluid dissolved numerous channels out of the crystal from the lateral prism surfaces and the upper fracture surface. A deep groove formed on one side of the crystal, extending into the core zone and allowing the fluid to dissolve a large part of the apparently more soluble teal-coloured inner core zone of the crystal (ESM 11f). This was followed by incomplete healing with blue tourmaline material. Many of the narrower channels healed from the outside, whereas the deeper cavities in the crystal remained hollow – especially the core zone of the crystal (ESM 11e).

## 4. Discussion

The study of corroded and subsequently healed tourmaline crystals using slice stacks that describe the entire internal architecture of the crystal provides deeper insights:
- into the morphology of the intermittently etched crystal.
- into the ways such crystals may heal.
- into the conditions of tourmaline formation within pegmatite miaroles with regard to supersaturation and corrosive phases of the fluid.

There was no example showing any sign of recrystallization. All crystals show growth, partial dissolution and a new growth period filling the corroded sections, summarized with the word “healing”.

### *4.1. Shapes of the etched intermediate state of the tourmaline crystals*

In their reconstructed corroded state, most of the tourmaline crystal examples 1–12 look similar to the corroded tourmaline crystals described by Rustemeyer (2026). Figure 11 provides a graphical summary on the diversity of the inner architecture of corroded and subsequently healed tourmaline crystals. Note that examples for the texture k

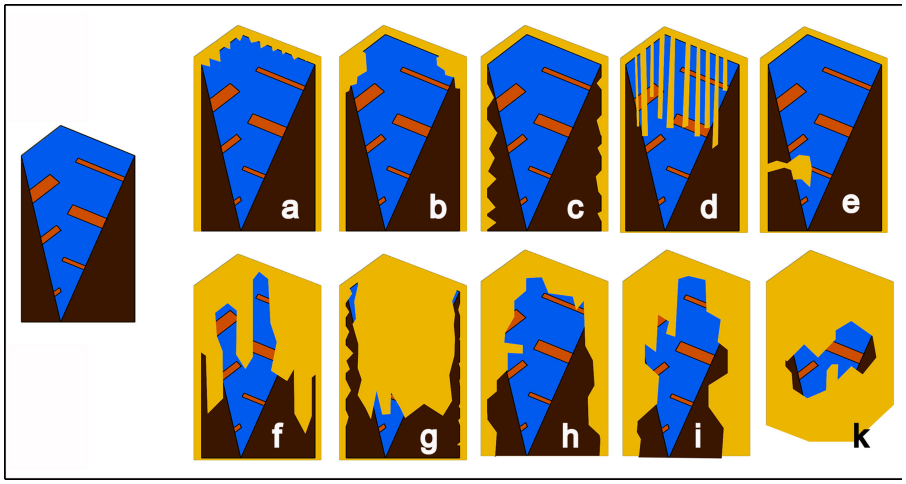



**Fig 11** Schematic drawings of the various types of corroded and then healed tourmaline crystal, left: original crystal: **a** – crystal with etch pits; **b** – crystal with corroded edges between prism and pyramidal faces; **c** – crystal with corroded prism faces (very rare); **d** – crystal with narrow tubes etched deeply into the pyramidal core area; **e** – crystal deeply corroded from the side; **f** – heavily corroded crystal with eroded columns in the core area; **g** – selectively corroded core area with slightly etched pyramid faces; **h–k** – dissolution bodies without remnants of original outer surfaces.

in Fig. 11 were not among the samples and discussed above and have not yet been observed from Skardu. The extremes in the given examples are quite deep and tight cavities in the crystal (*i.e.*, examples 7, 8and 9). In the same crystals, extremely fine columns and pillars survived the corrosion. These phenomena could be caused by interfering step and screw dislocations developing a narrow spiral parallel to the c-axis (Heimann 1975) and forming a channel which is under tension. Relaxation of this internal stress contributes to the dissolution energy during corrosion. The unstressed walls remain untouched, or they may be even protected by a layer of unsolvable material. As described by Rustemeyer (2026), when looking at fine needles in corrosion cavities of tourmaline crystals, one might wonder whether these may have grown onto the corroded crystal at a later stage. Here, in the case of the corroded and then healed tourmaline crystals, it can be clearly observed in the thin sections that these fine structures are parts of the original crystal since their small areas complement the larger remaining areas well in terms of colour and texture of examples 7, 8 and 9. Example 12 (ESM 11) is an outlier in terms of corrosion of the prism surfaces. In most cases, the prism surfaces resist corrosive attack from the outside; the core zones are significantly more affected. Possible reasons for their greater stability are discussed by Rustemeyer (2026).

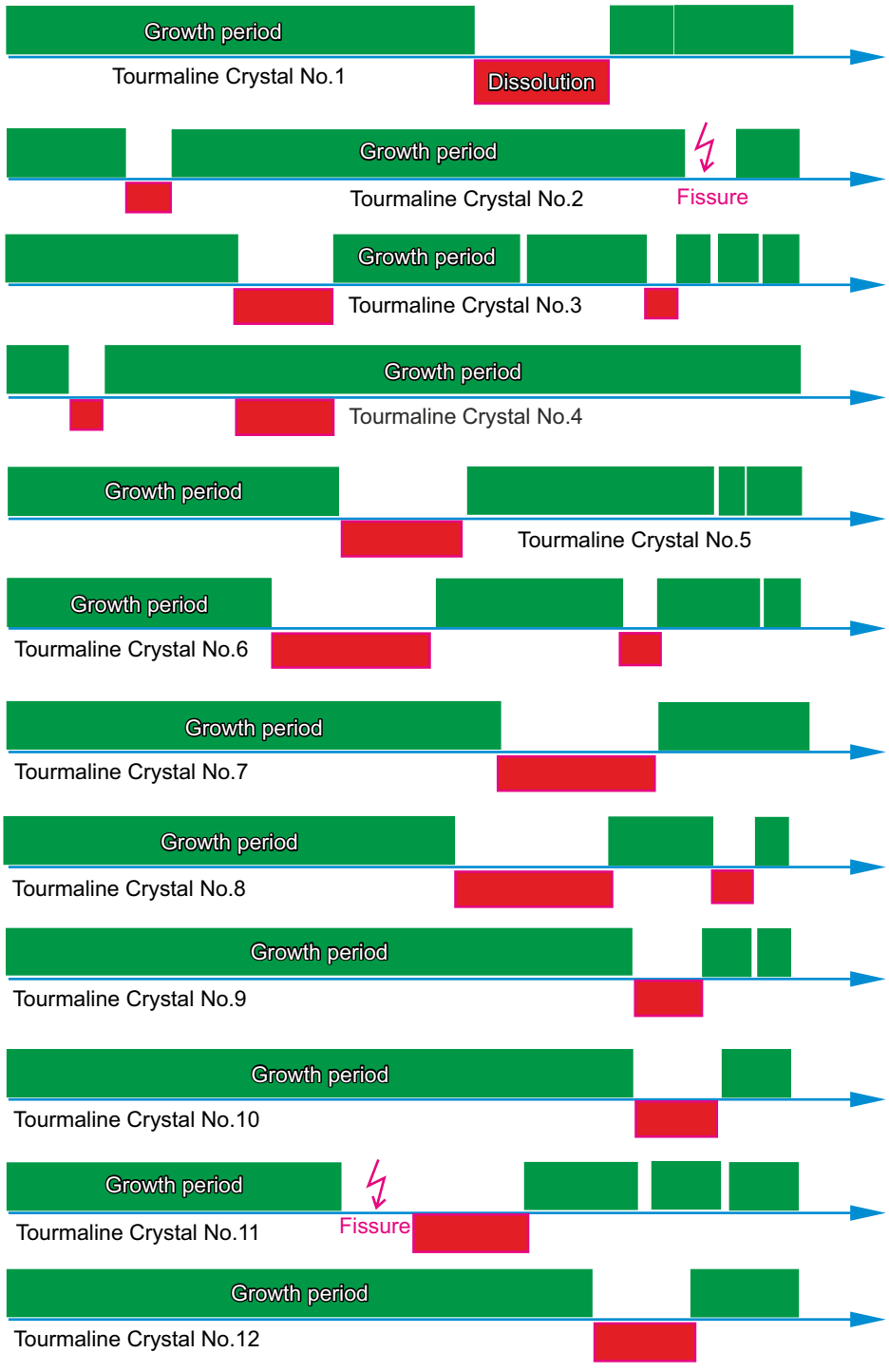



**Fig. 12** Development lines of the Schorl crystal examples No. 1–12 with growth periods (green), corrosion periods(red) and fissures (pink flash). The arrow represents the progression. The surface of the rectangles is an estimate proportional to the crystallized of corroded quantity of tourmaline mass.

## 4.2. Growth of the healing layers

Crystal growth and dissolution are inverse processes – at first glance, one might imagine that according to the correspondence principle the crystal corrodes in the same way that it previously grew, and that its way of growth is repeated when the corroded crystal heals. This is not the case for two reasons:

During growth under conditions of low supersaturation, edge and screw dislocations in the crystal lattice allow a constant rate of crystallization, as permanently favourable edge places are available to attach on the crystal lattice (Heimann 1975; Sangwal 1987). The crystal fills the entire faces as it continues to grow. During corrosion, the solution attacks the crystal preferably along the dislocations under tension and etches deep holes into the otherwise untouched surfaces.

Since tourmaline crystals grow in a pegmatite vein cooling down by several hundred degrees, the processes of growth, corrosion, and recrystallization run under very different conditions. Large parts of the tourmalines crystallize at high temperatures in melt, when the crystal still has significant growth rates on the prism faces. During healing, the temperatures are often lower, so the tourmaline grows mainly on its terminations in the direction of the c-axis. This means that healing at lower temperatures should start from faces with a component perpendicular to the prism faces. Thus, tubular cavities that were eroded deep into the crystal parallel to the c-axis have a good chance of growing seamlessly from the bottom of the hole and eventually to fill the hole entirely. If growth were possible on the lateral prism faces of the holes, it would be likely that the walls close to the opening would grow and close the hole – the space below would remain hollow. However, this is only observed in exceptional cases. In the crystal from example 12 many holes were etched horizontally into the rim area. In this case healing takes place close to the orifice on the top and bottom of the horizontal hole and closes it – leaving a void in the crystal.

Accordingly, wall layers (prismatic overgrowth) are only rarely found within the structures of the healing zones. In some cases, the relief of the corroded crystal surface on which the new layers grow influences the pattern of the regrown layer. As shown in ESM 10, the new tourmaline layers simply overgrow the etched-out faces and build-up sectors from these faces. This can be observed in thin section when the sectors have different colours as in ESM 10a and c. In other cases, individual crystals nucleate and grow within the healing zone and reveal with their own sectors the shape for regrowth (Examples in Fig. 5f; ESM 5c, 10c). Between these areas of individual regrowth there are many homogeneously coloured tourmaline layers filling the space in the healing zones.

### 4.3. Implications for the conditions in the pegmatitic fluids

All examples of tourmaline crystals presented here grew in pockets in one of the numerous pegmatite veins in the Skardu area. These crystals therefore allow conclusions to be drawn about the chronological sequence of growth and corrosion phases in the pockets in question.

In order to illustrate the saturation status of the fluid for the presented crystal examples, growth and corrosion periods were graphically represented along a line of evolution, approximately in the ratio of the respective grown or dissolved crystal masses (Fig. 12). In a future study analytical data and precise volume ratios could be determined.

With its revealing internal structure and the methodology of exploring the entire crystal structure through a set of slices, it is now possible to draw conclusive interpretations on the chronological sequence of growth and corrosion phases of tourmaline crystal in a pocket.

The trigger for growth is the supersaturation of the fluid with tourmaline building blocks. Possible triggers for corrosion were already presented in the first part of the paper: the exsolution of a supercritical aqueous fluid from the silicate melt, in which tourmaline matter is undersaturated. This is probably the cause of the severe corrosion cases.

## 5. Outlook

Purely morphological studies have their limitations. Through analytical work on the crystal slices, more precise statements could be made as to whether, for example, the healing tourmaline building blocks originate from inside of the pocket in a closed system, from another area of the pegmatite, or from the surrounding country rock. Of course, it would be best to study the pocket containing the tourmaline crystals in order to document the geological situation on site, i.e., the volume and shape of the pocket, the total amount of tourmaline crystals and their shapes, the paragenesis, fissure connections with the surrounding area, etc. and to combine it with compositional data and outer as well as internal and external tourmaline morphologies. With dissolution experiments in aqueous phase at lower temperature and pressure it could be studied, if etch pits, grooves and hillocks form at more mild temperature/pressure in the end phase of cooling of the pegmatite. If this article has sparked interest in the topic among colleagues, the author will make thin sections available for collaborative projects.

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