

Characterisation of Cu-bearing Tourmaline from Ethiopia, and Implications for Geographic Origin Determination

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ABSTRACT: In June 2026, a new deposit of Cu-bearing tourmaline was reported from Abulo Rukessa (or Abuloo) in the Guji Zone of southern Ethiopia. Fourteen stones reportedly from the discovery, including five faceted and nine rough samples, were characterised by standard gemmological testing, microscopy, polarised UV–Vis–NIR and Raman spectroscopy, and LA–ICP–TOF–MS. Their chemical composition was then compared to 1,653 analyses of 469 Cu-bearing tourmalines from Brazil, Mozambique and Nigeria acquired with the same instrument. All 14 Ethiopian stones belonged to the elbaite–fluor-elbaite series, and Cu exceeded Fe in 82 of the 83 individual spot analyses, which gave ranges of 373–26,157 ppmw Cu (0.05–3.27 wt.% CuO) and 2–7,368 ppmw Fe (up to 0.95 wt.% FeO). The data were divided into three categories based on bismuth content: high (3,214–15,088 ppmw Bi), intermediate (280–1,272 ppmw Bi) and low (28–105 ppmw Bi)—separated by two intervals into which no analysis fell. The same Bi tiers recurred from stone to stone and coexisted within single samples as growth zoning. Vanadium gave the clearest origin criterion: our Ethiopian specimens contained 42.9–146 ppmw of V compared to, at most, 20.3 ppmw in the samples from other origins. Statistical processing of the chemical data using a t–SNE algorithm showed that the Ethiopian analyses occupied a well-defined field separate from those of the other origins. The rare-earth element patterns were enriched in light REE and had mild Eu anomalies (Eu/Eu^* 0.40–1.06). Representative ordinary-ray Vis–NIR spectra showed greater absorption at 900 nm due to Cu^{2+} than at 700 nm due to $\text{Cu}^{2+} + \text{Fe}^{2+}$ ($\text{Abs}_{700}/\text{Abs}_{900}$ = about 0.56), and thus the analysed faceted specimens may be called ‘paraiba tourmaline’ according to LMHC guidelines.

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Paraiba-type tourmaline—Cu-bearing elbaite or liddicoatite displaying bright blue-to-green or yellowish green colouration of medium-light to high saturation and tone—has captivated dealers, collectors and enthusiasts around the world since it first appeared on the gem and mineral market in the late 1980s. Under the definition adopted by the Laboratory Manual

Harmonisation Committee (LMHC 2023), the variety name ‘paraiba’ applies to tourmaline of a restricted colour range that is derived mainly from Cu together with Mn, irrespective of geographic origin. This tourmaline variety was originally discovered by Heitor Barbosa in a weathered pegmatite near the village of São José da Batalha in the Brazilian state of Paraíba, from which the name



Figure 1: These five faceted Cu-bearing tourmalines (1.22–3.70 ct) from the new Ethiopian occurrence were examined for this study. The stones range from blue to greenish blue, locally with near-colourless zones. Sample numbers correspond to those in Table I. Individual images were resized and digitally arranged for comparison, so they are not shown to scale. Composite photo by SSEF.

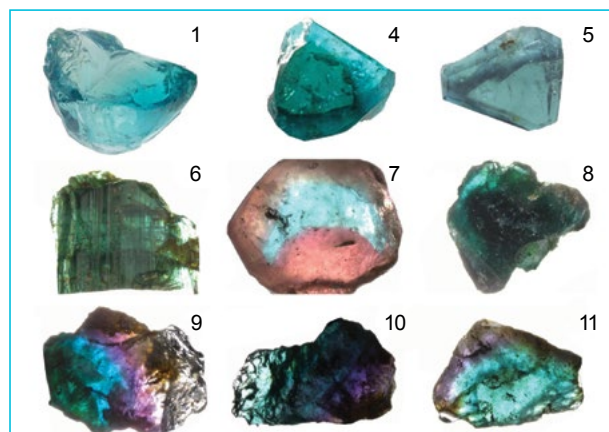


Figure 2: Nine rough Ethiopian Cu-bearing tourmalines (0.37–1.94 g) were also examined for this study. For samples 4 and 5, only their appearance after heat treatment (and polishing) is shown here. Sample numbers correspond to those in Table I. Individual images were resized and digitally arranged for comparison, so they are not shown to scale. Composite photo by SSEF.

is taken, and it immediately attracted worldwide attention for its exceptionally vivid colours, often described in the trade as ‘neon’ or ‘electric’ (Fritsch *et al.* 1990).

Production of this tourmaline variety from the original Brazilian locality and in the neighbouring state of Rio Grande do Norte has remained limited (Shigley *et al.* 2001). Subsequently, commercially important discoveries of Cu-bearing tourmaline occurred in Nigeria (Smith *et al.* 2001) and, in the early 2000s, within alluvial deposits near Mavuco, on the eastern side of the Alto Ligonha pegmatite district in Mozambique (Abduriyim *et al.* 2006; Laurs *et al.* 2008). Mozambique, in particular, came to supply gem-quality material in far larger quantities and, at times, in exceptional sizes. With more than one source producing visually indistinguishable stones, geographic origin determination of Cu-bearing tourmaline became a routine, albeit challenging, request for gemmological laboratories. The high-Cu material from Nigeria, commonly referred to in the trade as Nigerian type I, shows a colour range similar to that of Brazilian Cu-bearing tourmaline, whereas the lighter Nigerian type II material contains less Cu and more Pb (Abduriyim *et al.* 2006). Classical microscopy and standard spectroscopy rarely resolve such overlaps, and origin determination relies primarily on quantitative trace-element analysis (Abduriyim *et al.* 2006). More recently, machine-learning approaches have been applied to multi-element chemical data for gemstone origin determination. These include supervised classification against labelled reference datasets for ruby and sapphire (Seneewong-Na-Ayutthaya

et al. 2025) and unsupervised visualisation of 57-element datasets for Cu-bearing tourmaline, in which unknown analyses are compared with clusters anchored by reference samples (Wang *et al.* 2025). Both of these machine-learning approaches evaluate multivariate chemical patterns rather than relying on individual element limits.

In mid-2026, Ethiopia emerged as a new source of Cu-bearing tourmaline (e.g. Figures 1 and 2). This discovery unfolded within a few months: A stone of undisclosed origin was submitted to SSEF in April 2026, and its trace-element composition could not be assigned confidently to any of the established reference populations from Brazil, Nigeria or Mozambique. As no Ethiopian reference population existed at that time, SSEF withheld an opinion on the geographic origin for this and similar stones in the following weeks. (Subsequently, such tourmaline could be attributed to the new deposit, using the techniques described in this article.) In June 2026, reports of alluvial Cu-bearing tourmaline workings in Ethiopia reached the trade, and rough material declared as Ethiopian began to appear on the market. On 18 June 2026, SSEF publicly announced the reported new source (SEEF 2026). Subsequently, on 26–27 June, two preliminary studies appeared online: (1) Pardieu *et al.* (2026) examined 21 stones obtained on the Bangkok gem market, and found that Fe contributed substantially to the colour of many of them, also noting comparatively elevated Ga, Zn, Pb and Bi; and (2) the DSEF German Gem Lab analysed about 50 samples, and found higher Ca, Fe, Ga and Pb than in Brazilian material (DSEF 2026). On 27 August 2026, a joint press release from the

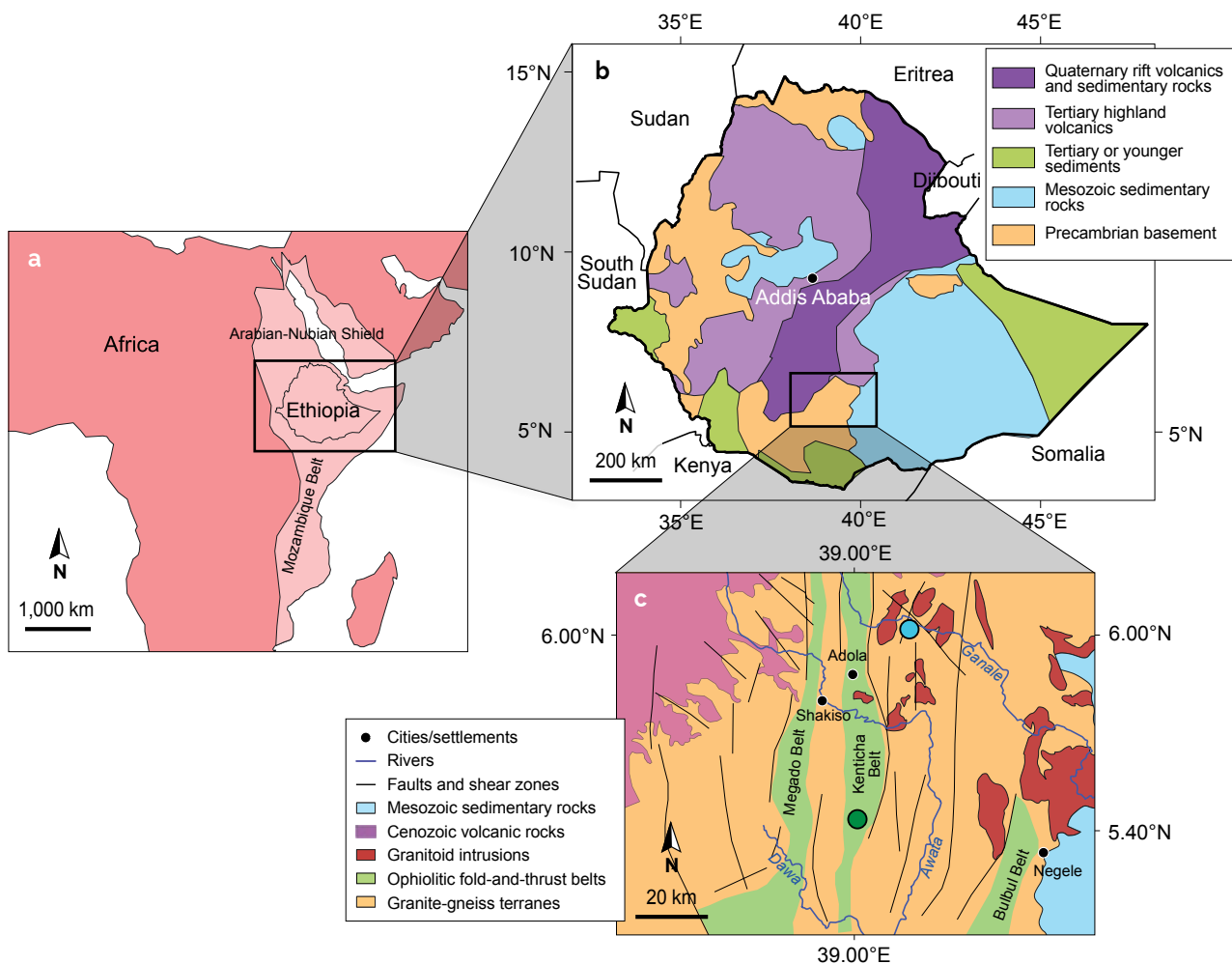


Figure 3: Three maps show the geological setting of the Abulo Rukessa tourmaline occurrence. (a) An overview map provides the location of Ethiopia in Africa. The light pink area shows the extent of the Pan-African East African Orogen, which consists of the Arabian-Nubian Shield in the north and the Mozambique Belt to the south and east. (b) The main geological subdivisions are seen on a map of Ethiopia (modified after Tadesse *et al.* 2003 and Hagos *et al.* 2020). The Abulo Rukessa tourmaline mining area is hosted by Precambrian basement rocks. (c) On a simplified geological map of the Adola region, the light blue dot marks the location of the Abulo Rukessa tourmaline deposit, and the green dot denotes the position of the Shakiso emerald deposit. Modified after Mohammedyasin (2017). Geological maps were modified from ones provided by the Czech Geological Survey (<https://mapy.geology.cz/ethiopia1mil/?locale=en>).

Gemological Institute of America and the Gübelin Gem Lab reported elevated concentrations of V, Ga and Pb in the Ethiopian material (GIA 2026).

The first report on the deposit itself—near Abulo Rukessa (or Abuloo) in the Guji Zone of the Oromia Region (Figure 3)—was compiled during a field visit on 26 June and published on 4 July (Sisay 2026). On 17 July, an independent trade account described rough material attributed to the new source being examined and purchased in Addis Ababa and Hawassa during a late-June visit, although those merchants did not reach the mining site (Okabe 2026). At the same time, the Central Gem Laboratory in Tokyo, Japan, published a preliminary

study of 26 samples in which every stone proved Cu-bearing, with Cu rather than Fe as the dominant chromophore, and reported that the material could be separated from other origins by trace-element analysis (Emori & Kitawaki 2026).¹

The early studies agreed that the Ethiopian deposit produces a chemically heterogeneous population of Cu-bearing tourmaline. Pardieu *et al.* (2026) distinguished stones in which Cu was the dominant chromophore (and which satisfied LMHC's criteria for 'paraiba' tourmaline), as well as a transitional group of debatable classification, with some Fe-rich stones that are better described as indicolite. The DSEF German Gem Lab classified

¹ Editor's note: An English-language version of this report is available in the Gem Notes section of this issue (see pp. 227–230).

fewer than half of their approximately 50 specimens as ‘Paraíba tourmaline’; the remainder were either Cu-free or contained too much Fe relative to Cu (DSEF 2026; see also Milisenda & Guo 2026). The 26 samples studied by Emori and Kitawaki (2026) had been identified as ‘Paraíba tourmaline’ before analysis, performed partly in the field with a portable spectrometer (i.e. the absorption feature near 900 nm was stronger than that near 700 nm). These three studies are based on differently assembled sample sets, covering material ranging from unselected market lots to stones already identified as Paraíba-tourmaline.

Both the laboratory studies and field report describe a production that varies markedly from stone to stone (Emori & Kitawaki 2026; Pardieu *et al.* 2026; Sisay 2026), and multi-coloured rough specimens have also been illustrated (Milisenda & Guo 2026). It is not known whether the element enrichments proposed as markers of Ethiopian origin (Ga, Pb and V, together with the Bi reported from the first-marketed stones) are representative of this deposit as a whole, or only particular growth zones in the samples. Separation of the Ethiopian Cu-bearing tourmaline from Brazilian, Mozambican and Nigerian stones was performed by Emori and Kitawaki (2026) by plotting Ga vs Pb and Ga vs V, and by linear discriminant analysis of 27 elements.

In the present study, we review the geological setting of the deposit area and briefly provide

first-hand observations of the mine workings. Then we characterise 14 specimens of the Ethiopian Cu-bearing tourmaline (see Figures 1 and 2, and also Table I). In addition to collecting their gemmological properties and performing ultraviolet-visible-near infrared (UV-Vis-NIR) and Raman spectroscopy, particular emphasis was placed on evaluating spot-resolved chemical analyses of the samples. We assessed each stone against the LMHC criteria for ‘paraíba tourmaline’, examined chemical variations within and between samples, and finally placed the Ethiopian analyses within our comparison dataset (Wang *et al.* 2025) to separate them from those of other global localities.

GEOLOGICAL SETTING

Ethiopia is a landlocked country in the Horn of Africa bordering Kenya, South Sudan, Sudan, Eritrea, Djibouti and Somalia (Figure 3a, b). Geologically, Ethiopia sits at the north-western termination of the Mozambique Belt, an orogenic region extending about 4,000 km from eastern Antarctica in the south to the Arabian Peninsula in the north. The formation of this belt (ca. 1,100 to 480 million years ago [Ma]) during the amalgamation of Gondwana in the Pan-African orogeny (Grantham *et al.* 2003) produced important deposits of coloured stones, such as the Cu-bearing elbaite from Mavuco and the Cu-bearing liddicoatite from

Table I: Cu-bearing tourmaline samples reportedly from Ethiopia examined in this study.

Sample no.	Form	Weight	Colour	Declared treatment
ETH_1	Rough	~1 g	Greenish blue with a near-colourless zone	Unheated
ETH_2	Faceted	3.70 ct	Blue with a near-colourless zone	Not declared
ETH_3	Faceted	1.22 ct	Blue	Not declared
ETH_4 ^a	Rough	0.99 g	Bluish green with a blue rim	Heated
ETH_5 ^a	Rough	0.50 g	Bluish green	Heated
ETH_6	Rough	1.94 g	Bluish green	Unheated
ETH_7	Rough	0.89 g	Blue to orangey pink	Unheated
ETH_8	Rough	0.89 g	Dark bluish green to greenish blue	Unheated
ETH_9 ^b	Rough	0.60 g	Green, blue, purple, pink and near-colourless	Unheated
ETH_10	Rough	0.48 g	Bluish green to blue to purple	Unheated
ETH_11	Rough	0.37 g	Bluish green to greenish blue to purple	Unheated
ETH_12	Faceted	2.03 ct	Blue	Heated
ETH_13	Faceted	1.28 ct	Greenish blue	Heated
ETH_14	Faceted	1.83 ct	Light blue	Heated

^a Samples ETH_4 and ETH_5 were received as heated and partially polished, but their original rough condition is shown in Figure DD-1 in *The Journal's* data depository.

^b Later cut in half along the c-axis.

Maraca in north-eastern Mozambique (Laurs *et al.* 2008; Karampelas & Klemm 2010; Katsurada & Sun 2017). In Ethiopia, the Pan-African (mostly Precambrian-aged) basement is exposed in four different areas of the country (Figure 3b), and is mainly composed of gneisses and migmatites, volcano-sedimentary and ophiolitic assemblages, and various granitoids (Yibas *et al.* 2002; Tadesse *et al.* 2003). Regional subsidence and marine transgressions during the Late Paleozoic to Early Mesozoic overlaid these Precambrian basement rocks with a thick sedimentary cover, which is mostly preserved in south-eastern Ethiopia today (Figure 3b; Tadesse *et al.* 2003). Since Eocene time (ca. 45 Ma), the opening of the East African Rift System has led to widespread volcanic activity and the deposition of basaltic to alkaline volcanic rocks in the central to northern parts of the country (Figure 3b; Ebinger *et al.* 1993; Feyissa *et al.* 2019).

In the southern Precambrian exposure of Ethiopia, two distinct geological terranes are recognised (Figure 3c): (1) a granite-gneiss terrane, comprising high-grade paragneiss and orthogneiss, migmatite, and amphibolite; and (2) ophiolitic fold-and-thrust belts, including the Megado and Kenticha belts, which contain mostly metamorphically overprinted island-arc basalt, serpentinite and amphibolite (Ghebreab 1992; Yibas *et al.* 2002; Mohammedyasin 2017). The two terranes are separated by approximately north-south-trending shear zones (Ghebreab 1992; Yibas *et al.* 2002). During the late stages of the Pan-African orogeny (ca. 570–520 Ma), late- to post-collisional granites and pegmatites intruded both the granite-gneiss and the ophiolitic terranes (Küster *et al.* 2009; Mohammedyasin 2017).

The mining area for Cu-bearing tourmaline (6°01'17" N, 39°09'50" E; derived from Sisay [2026] on Google Maps) lies near the village of Abulo Rukessa (or Abuloo), Guji Zone, Oromia Region in south-central Ethiopia (Figure 3c). It is situated about 25 km north-east of Adola town (Kibre Mengist), about 40 km north-east of Shakiso and close to Ganale River. This region is well known for its economic mineral resources, particularly its primary and secondary gold deposits, and LCT (lithium-cesium-tantalum) rare-element pegmatites (Tadesse 1999; Mohammedyasin 2017). The best-known cluster of LCT pegmatites in this region (Kenticha) is located about 30 km south-east of Shakiso. Pegmatite deposits there are mined for Ta, as well as emeralds (Küster *et al.* 2009; Laurs & Strack 2017; Schluessel & Schuessel 2018). The most highly differentiated unit of the strongly zoned

Kenticha pegmatite is developed as a coarse-grained albite-quartz-spodumene-muscovite-microcline unit with accessory amazonite, apatite, Li phosphates, beryl, Li mica, topaz, cassiterite and Ta-rich oxide minerals (Küster *et al.* 2009), and is similar to the mineral paragenesis observed in the primary deposits of Paraíba tourmaline in Brazil (Beurlen *et al.* 2011). The Kenticha pegmatite has been dated by U-Pb on manganotantalite to ca. 530 Ma (Küster *et al.* 2009); Ar-Ar dating of emerald-bearing mica schists from Shakiso yielded similar ages of ca. 521 Ma (Nicol 2021).

The Cu-bearing tourmaline mining site at Abulo Rukessa (again, see Figure 3c) is located in a north-north-east trending fault zone cross-cutting the Ganale River, and is close to three outcrops of leucocratic, coarse-grained granites. Tourmaline is found in yellow-tinged, heavily weathered secondary surface soils down to a depth of 6 m (Sisay 2026). The condition of the rough material, which ranges from alluvially rounded stones to crystals with well-preserved prism faces and striations (see below), indicates a deposit that is alluvial to eluvial in nature. However, no primary host of the Cu-bearing tourmaline has yet been documented, and the relationship between the recovered material and the nearby granitic and pegmatitic bodies remains unknown.

MINING

During a visit to the locality by one of the authors (TS) in June–July 2026 (Figure 4), mining was confined to secondary deposits developed along a creek valley, where the tourmaline gems were recovered from unconsolidated gravel using simple hand tools and shallow excavations. Numerous pits had been opened along the valley floor by local miners. The surrounding hills are a possible target in the search for the primary source of the tourmaline.

Shortly after the discovery, mining and trading were conducted informally by members of the local community without legal mining licences. Material ranging from commercial-grade rough to high-quality gem crystals became available within a short period, attracting local gemstone traders and international buyers. As production increased and commercial interest expanded, the relevant government authorities initiated measures to regulate mining activities and began processing applications for mining rights. As early as April 2026, the Ethiopian Mining Cadastre listed several applications for tourmaline-mining licences (Sisay 2026). Reliable cumulative production figures are currently unavailable.



Figure 4: (a) Several motorbikes used by miners and traders are parked near the entrance to the Abulo Rukessa mining area. (b) Local miners have opened several hand-dug pits in the area. A policeman (blue shirt) is patrolling the area. Photos by T. Sintayehu, June–July 2026.

MATERIALS AND METHODS

Samples

Between April and July 2026, we studied 14 pieces of Cu-bearing tourmaline reported to have originated from the new mining area in Ethiopia (see Table I). The specimens consisted of five faceted stones (1.22–3.70 ct) submitted by clients and nine rough samples (0.37–1.94 g) that were purchased for research. Although none of the specimens analysed in this study were collected *in situ* under documented geological control, they were obtained from trusted clients and suppliers connected to the Ethiopian material. Five samples were declared heated, seven were reportedly unheated, and the treatment status of two samples was not indicated (again, see Table I).

The rough samples were polished perpendicular to the *c*-axis, so that every specimen, faceted or rough, presented at least one flat, cleaned surface for chemical analysis. Rough sample ETH_9 was subsequently cut parallel to the *c*-axis, exposing a surface on which several colour zones could be analysed.

Methods

All analytical work was carried out at SSEF, using the techniques described below. Where present, and where possible, individual colour zones within a specimen were analysed separately.

Standard Gemmological Testing and Microscopy.

Refractive indices and birefringence were measured on the faceted stones and on polished surfaces of the rough samples with a standard gemmological refractometer, and SG was determined hydrostatically. Reactions to UV radiation were observed under long-wave (365 nm) and short-wave (254 nm)

UV lamps. Internal features were examined with a gemmological microscope using darkfield, brightfield and fibre-optic illumination.

Raman and Photoluminescence Spectroscopy.

Raman micro-spectroscopy was carried out on all samples with a Renishaw inVia spectrometer using 514.5 nm laser excitation at 50% laser intensity, a long-working-distance 20× objective, 10 s integration time and one accumulation. For zoned crystal ETH_9, all five colour zones (near-colourless, pink, purple, blue and green) were measured with the laser polarisation parallel to the *c*-axis. Three spectral windows were recorded per measurement point: the tourmaline fingerprint region (about 150–1400 cm⁻¹), the OH-stretching region (about 3000–4000 cm⁻¹) and a 7500–8500 cm⁻¹ Raman-shift window in which REE photoluminescence (PL) appears (about 838–914 nm with 514.5 nm excitation). Inclusions and secondary residues in hollow channels and tubes were identified by Raman point analyses. The PL spectra were baseline-corrected (asymmetric least squares), cleaned of spike artefacts and normalised so that relative intensities remained comparable.

UV-Vis-NIR Spectroscopy.

Polarised UV-Vis-NIR spectra were collected in the 290–1200 nm range with an Agilent Cary 5000 spectrophotometer and a Varian Cary 500 spectrophotometer. The stones were crystallographically oriented, and ordinary-ray (E_{⊥c}) spectra were recorded on all 14 stones. Individual colour zones were measured separately where sample geometry permitted; otherwise, the resulting spectra represent the combined absorption of the colour zones. The spectra were processed as follows: the

detector changeover at 850 nm (Cary 5000) or at 800 nm (Cary 500) was excluded, and the offset between the two detector segments was corrected by matching the linear trends on either side; each spectrum was shifted so that its minimum absorbance over the analysed range equalled zero (minimum-shifted absorbance). Because the spectra were not normalised to path length, absolute absorbance values are not quantitatively comparable between samples. We report the ratio Abs_{700}/Abs_{900} , where Abs_{700} is the absorbance at 700 nm in which Cu^{2+} and Fe^{2+} absorptions overlap, and Abs_{900} is the absorbance at 900 nm, where Cu^{2+} absorbs with minimal Fe^{2+} interference (Merkel & Breeding 2009; Krzemnicki & Wang 2022). The ratio is model-free and involves no band fitting. According to LMHC Information Sheet No. 6, an Fe-rich Cu-bearing tourmaline is excluded from the ‘paraiba’ designation when $Abs_{700}/Abs_{900} > 1$ in the ordinary-ray spectrum, whereas values below 1 do not meet this exclusion criterion.

LA-ICP-TOF-MS Analysis. Chemical analysis of all samples was carried out by laser ablation inductively coupled plasma time-of-flight mass spectrometry (LA-ICP-TOF-MS; GemTOF platform), using a 193 nm ArF excimer laser-ablation unit (NWR193UC, ESI, USA) coupled to an ICP-TOF-MS (icpTOF R, Tofwerk AG, Switzerland). The set-up, tuning and quantification strategy were described by Wang and Krzemnicki (2021) and Wang *et al.* (2025). Following a detector change that improved sensitivity, a 75 μm spot was used (instead of the 100 μm spot employed previously) to obtain comparable signal intensity. Otherwise, the same parameters were used: 600 laser shots at 20 Hz with a fluence of about 5.6 J/cm², five pre-cleaning shots and He as carrier gas. The TOF analyser records the entire mass spectrum from $^7Li^+$ to $^{238}U^+$ simultaneously (mass resolution of about 3,000 at $^{238}U^+$); nearly all elements were quantified for every spot, with per-spot limits of detection (LOD) exported. Calibration used NIST SRM 610 and 612 glasses as external standards, measured before and after the samples to monitor drift, with $^{29}Si^+$ as an internal standard followed by total-mass normalisation (Wang *et al.* 2025 and references therein). In total, 83 spots on the 14 stones (4–11 spots per specimen) were analysed to sample individual colour zones on polished or cleaned surfaces.

The Ethiopian analyses were compared with the reference dataset assembled from samples of Cu-bearing tourmaline in SSEF’s collection, the Prof. Henry A. Hänni collection, client stones and mining-company material. The dataset included 1,653

analyses of 469 stones, comprising Brazil (253 stones, 826 analyses), the Mavuco area of Mozambique (129 stones, 502 analyses), the Maraca area of Mozambique (72 stones, 275 analyses) and Nigeria (15 stones, 50 analyses). Together with the 83 Ethiopian analyses, our dataset therefore comprised 1,736 analyses of 483 stones. The two Mozambican populations differ in species: the Mavuco material is fluor-elbaite, whereas the Maraca material is fluor-liddicoatite (e.g. Wang *et al.* 2025), so they were kept as separate groups throughout.

Data Processing and Statistical Analysis. All statistical analyses included the same 57 elements (from Li to U) used by Wang *et al.* (2025). Although the GemTOF instrument records the full mass spectrum, elements affected by interferences or by frequent non-detection were excluded. Since the t-distributed stochastic neighbour embedding (t-SNE) algorithm measures pair-wise similarities and uses a complete dataset, concentrations below LOD were replaced by random values drawn from element-specific log-normal distributions fitted to the positive LOD values, after which all concentrations were log₁₀-transformed (Wang & Krzemnicki 2021; Wang *et al.* 2025). This follows the convention of our previous dataset, so that the Ethiopian and the earlier analyses were plotted under the same pre-processing scheme. For values below LOD, random substitution avoided an artificial pile-up at a single value, which would result from using a constant substitute. Quantities read from a single element, such as the median REE patterns, instead used the conventional constant substitute LOD/2. The two-dimensional scatterplots and the chondrite-normalised REE ratios used detectable values only.

Ten elements were selected from the 57-element dataset for further statistical analysis: Bi, Pb, Be, Ga, Sn and Zn characterise the subgroup chemistry; Cu, Fe and Mn are relevant to colouration; and Nd represents the observed light-REE enrichment. Associations between pairs of elemental concentrations were evaluated using Spearman’s rank correlation coefficient (ρ), a measure that compares the rank order of the analyses rather than the concentrations themselves, so that it describes how consistently two elements rise and fall together. Values of ρ range from –1 (one element rises as the other falls) through 0 (no consistent relation) to +1 (the two rise and fall together). It was used here because the element concentrations span three orders of magnitude.

In the comparisons below, Cu and Fe are presented as measured mass concentrations rather than being

combined into a derived ratio. Copper was above LOD in all 83 Ethiopian analyses and Fe was above LOD in 81. In the remaining two analyses, the Cu concentration exceeded the Fe LOD, so the Cu–Fe comparison is unaffected by the treatment of censored values.

REE patterns were normalised to CI chondrite values (McDonough & Sun 1995). For the median patterns (see REE Systematics in the Results and Discussion section below), elements below LOD in more than 50% of the spots of a group were drawn as open symbols. The Eu anomaly is defined as $\text{Eu}/\text{Eu}^* = \text{Eu}_n/\sqrt{(\text{Sm}_n \times \text{Gd}_n)}$; the subscript n denotes chondrite-normalised values.

t-SNE Visualisation. The t-SNE algorithm arranges the data on a two-dimensional plot, so that compositionally similar analyses are plotted close together without using the origin labels in the calculation. (For more information about t-SNE, see Box B in Wang *et al.* 2025.) This algorithm was chosen because bivariate element plots and principal component analysis (PCA) showed substantial overlaps in elbaite origins for this dataset, whereas t-SNE resolved them. The comparison of methods and the choice of parameters were discussed by Wang *et al.* (2025).

For the global-locality t-SNE plot, the 83 Ethiopian analyses were appended as one origin group to the published workflow of Wang *et al.* (2025), giving 1,736 analyses of 483 stones in the 57-element space with the standardised-Euclidean metric computed from the global variances. The embedding used the exact gradient calculation rather than the Barnes-Hut approximation, with a perplexity of 30, a learning rate of 100, an early exaggeration factor of 30 (applied at the beginning of the optimisation process to enhance cluster separation), a maximum of 5,000 iterations and PCA initialisation—identical to the process used by Wang *et al.* (2025).

For the Ethiopia-only t-SNE plot, the same 83 analyses were recalculated independently, with the data standardised using variances derived from the Ethiopian analyses alone. The exact parameters were evaluated, and the final selected parameters included a perplexity of 30, a learning rate of 50, an early exaggeration factor of 12, a maximum of 5,000 iterations and PCA initialisation. The lower learning rate and the early exaggeration factor were selected for the substantially smaller dataset and were fixed before the subgroup labels were applied; they were not optimised to increase separation among the three bismuth-related subgroups discussed below.

In the t-SNE plots, the local arrangement of points

represents similarity in multi-element composition, whereas the axis values, orientation and distances between well-separated groups have no directly interpretable compositional meaning.

RESULTS AND DISCUSSION

Gemmological Characterisation

The colours of the faceted stones ranged from blue to greenish blue, with some visibly colourless areas (Figure 1). The homogeneous rough pieces were bluish green to greenish blue, whereas the zoned samples graded from green through blue and violet or purple to pink and to near-colourless (Figure 2). Some samples were declared as heat treated (Table I), and the appearance of two of them before and after heating (and polishing) is shown in Figure DD-1 (all figures and tables with the ‘DD-’ prefix are available in *The Journal*’s online data depository).

The faceted stones were of high clarity with very few inclusions, while the rough samples were mainly heavily included, with diaphaneity ranging from transparent to sub-translucent.

RI_o were $n_o = 1.639\text{--}1.645$ and $n_e = 1.620\text{--}1.625$, with a birefringence of $0.019\text{--}0.020$, and the hydrostatic SG was $3.04\text{--}3.08$. These values are consistent with the properties of gem tourmaline. All samples were distinctly pleochroic: stones that were blue in the o-ray appeared bluish green with a stronger yellow component in the e-ray, while the bluish green stones appeared darker bluish green in the e-ray.

All samples were inert to both long- and short-wave UV radiation, except for the colourless zones in four samples, which showed a yellow fluorescence to short-wave UV.

Microscopic Observations

Faceted Stones. The faceted samples commonly showed a gradual colour zoning from blue or greenish blue to near-colourless (Figure 5a), which was also present in rough sample ETH_1. Microscopic examination revealed delicate growth features, including fine growth lines (Figure 5a, b) and well-developed growth zoning (Figure 5c, d).

Very fine hollow needle-like structures oriented parallel to the *c*-axis were present in a few samples (Figure 6a), and some stones contained larger planar hollow channels partially filled with Fe-hydroxide or Fe-oxide residues (Figure 6b). Similar channels and tubes, either empty or filled with an Fe-rich secondary mineral, have also been documented in Cu-bearing tourmaline from Brazil, Nigeria and Mozambique (Abduriyim *et al.* 2006; Laurs *et al.* 2008). Networks

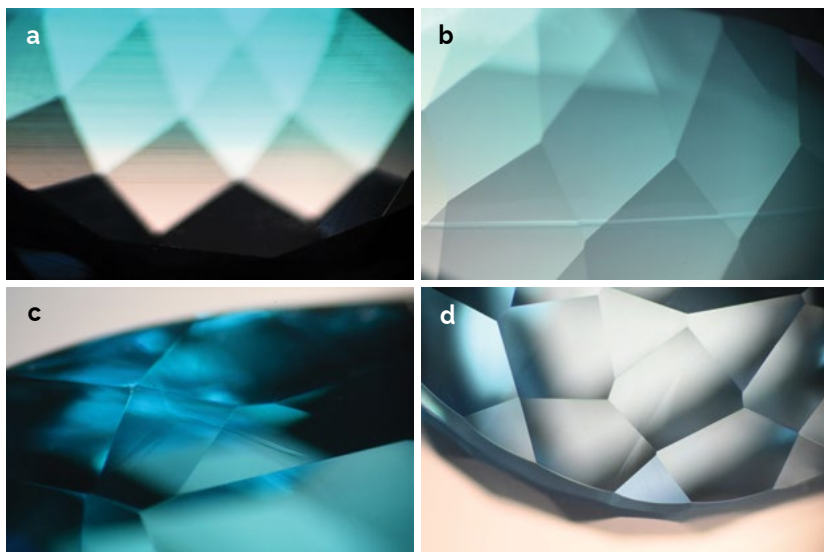


Figure 5: Growth features observed in the faceted Cu-bearing tourmalines from Ethiopia include (a) fine horizontal growth lines associated with gradual colour zoning from blue to near-colourless, (b) an individual growth line, (c) the intersection of three growth planes and (d) a single growth plane. Photomicrographs by SSEF; magnified 50 $\times$.

of irregularly shaped, locally elongated fluid inclusions, commonly referred to as ‘trichites’ (Figure 6c), were rare in the faceted stones but common in the rough material.

Rough Samples. The rough specimens were generally heavily included with fluid inclusions and fissures, and several showed distinct growth generations (e.g. a greenish blue core surrounded by a lighter rim), together with pronounced, eye-visible colour zoning (again, see Figure 2). Some colour zones were diffuse and irregular, corresponding only loosely to the crystal symmetry, whereas others followed it.

Hollow channels and tubes were common in the rough specimens, consistently oriented parallel to the *c*-axis and frequently filled with an Fe-rich residue (Figure 7a); Raman spectroscopy identified hematite in such a filling in ETH_4 (Figure DD-2). In several samples these planar hollow channels were bordered by a sharply defined brownish to slightly purplish layer (Figure 7b, c), confirmed by Raman spectroscopy to be tourmaline. This boundary was sharp rather than gradual, which can be explained more readily

as a growth feature rather than a radiation-induced feature such as reported previously in Cu-bearing tourmaline (e.g. Krzemnicki 2024).

A single solid inclusion was found in the entire sample suite: a small colourless crystal on a partially healed fissure in ETH_4 that was identified by Raman spectroscopy as feldspar (Figure 7d; Figure DD-2). Several samples contained relatively large, structured, wedge-shaped cavities oriented perpendicular to the *c*-axis, which were locally filled with granular residues that appeared dark in transmitted light and whitish in reflected light (Figure 7e, f). These were identified by Raman analysis as calcite.

Raman and PL Spectroscopy

Raman spectra of all stones were consistent with an elbaite assignment, with no differences between colour zones beyond intensity effects. The spectra obtained from zoned crystal ETH_9 are presented in Figure 8. The tourmaline fingerprint region (150–1400 cm^{-1}) showed identical elbaite spectra for all five colour zones (Figure 8a), and the spectra of the OH-stretching region were equally invariant (Figure



Figure 6: Additional internal features observed in faceted Ethiopian Cu-bearing tourmalines include (a) fine hollow needle-like structures oriented parallel to the *c*-axis, (b) planar channels partially filled with an Fe-rich substance and (c) a network of irregular fluid inclusions, locally developed as ‘trichites’. Image a shows ETH_3, for which the treatment status is unknown; images b and c depict ETH_13, reported as heat treated. Photomicrographs by SSEF; magnified 50 $\times$.

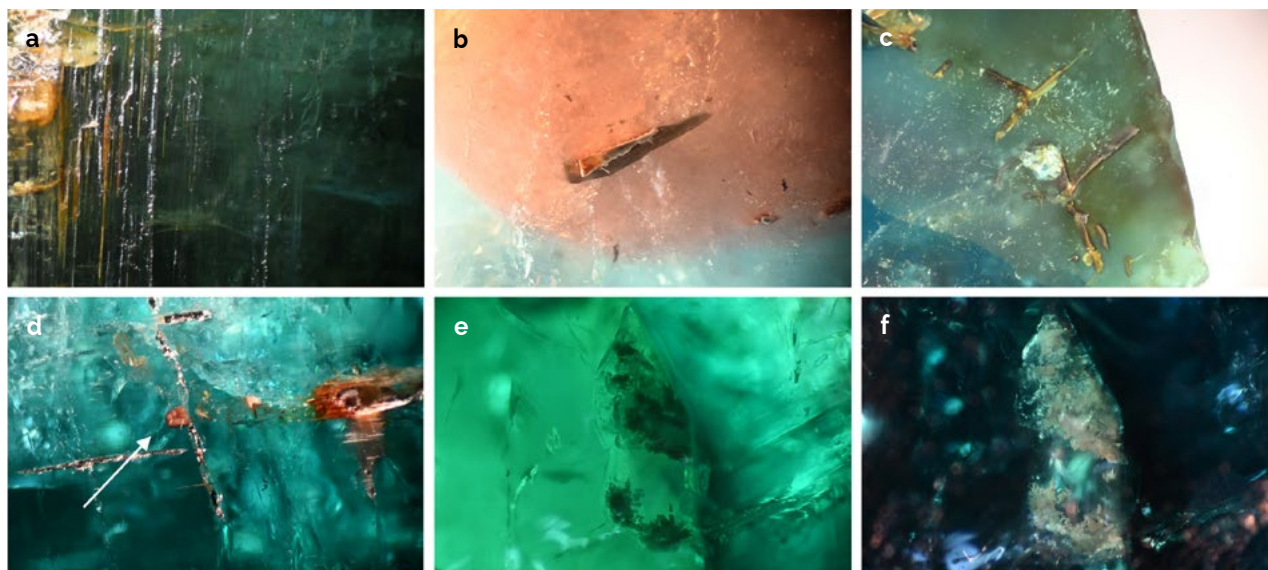


Figure 7: Internal features observed in rough Ethiopian Cu-bearing tourmalines include: (a) hollow channels oriented parallel to the c-axis and locally filled with an iron-rich residue; (b, c) planar hollow channels bordered by a brownish to slightly purplish tourmaline layer; (d) a small colourless feldspar (see arrow) on a partially healed fissure in ETH_4, which was the only solid inclusion found in our samples; (e) granular residues, identified as calcite, in a structured wedge-shaped cavity oriented perpendicular to the c-axis, appearing black in transmitted light; and (f) the same residues appearing whitish in reflected light. Images a–c show ETH_6, ETH_7 and ETH_9, respectively, reported as unheated; images d–f are of ETH_4, reported as heat treated. Photomicrographs by SSEF; magnified 50 $\times$.

8b). In the region encompassing REE luminescence, the PL spectra recorded an emission of variable intensity across the different colour zones (Figure 8c). The emission lies in the spectral region associated with Nd³⁺ (Lenz *et al.* 2013). Because the PL and LA-ICP-TOF-MS measurement points were not spatially co-registered, no quantitative relationship between emission intensity and Nd concentration is inferred here.

UV-Vis-NIR Spectroscopy

Ordinary-ray (E_{Lc}) UV-Vis-NIR spectra of two representative stones are shown in Figure 9. The spectrum of zoned rough specimen ETH_1 represents an average, since it was not possible to isolate an individual colour zone, whereas the spectrum of faceted sample ETH_14, which was not visibly zoned, represents a light blue colour. All the spectra showed two broad absorption bands, one near 700

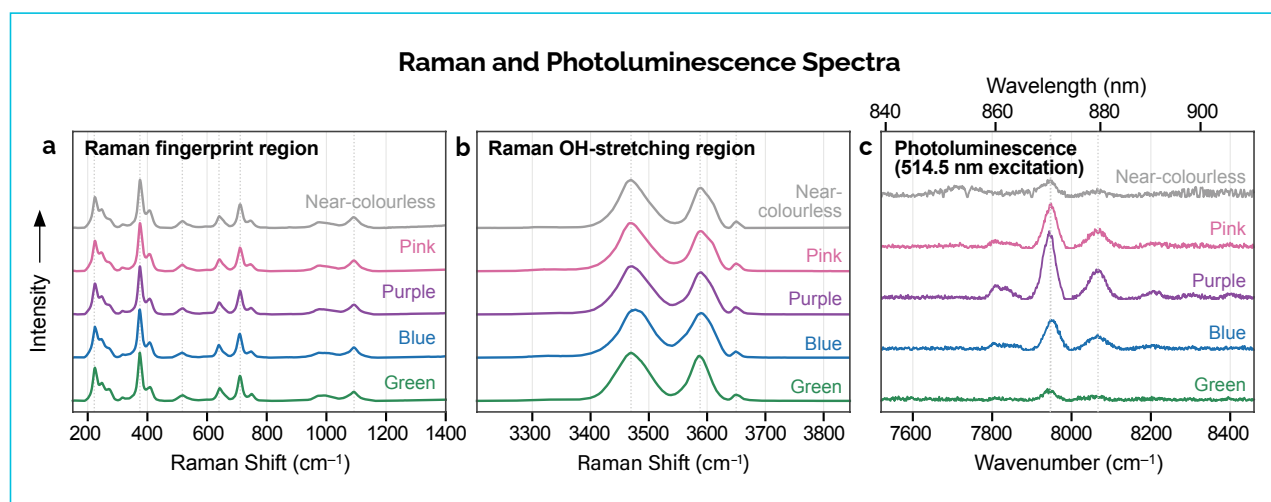


Figure 8: Raman and PL spectra (measured with the 514.5 nm laser polarised parallel to the c-axis) of zoned rough sample ETH_9, the only studied stone with analytical spots that span all three Bi-defined subgroups (SG1–SG3), were recorded for the five colour zones along the near-colourless to green traverse. (a) In the tourmaline fingerprint region, every zone shows the same elbaite pattern. (b) The spectra in the Raman OH-stretching region are, likewise, stable along the traverse. (c) The PL spectra in the 7500–8500 cm⁻¹ Raman-shift window (about 838–914 nm at 514.5 nm excitation) show variations in the intensity in the spectral region associated with Nd³⁺. All spectra are baseline-corrected, normalised and vertically offset.

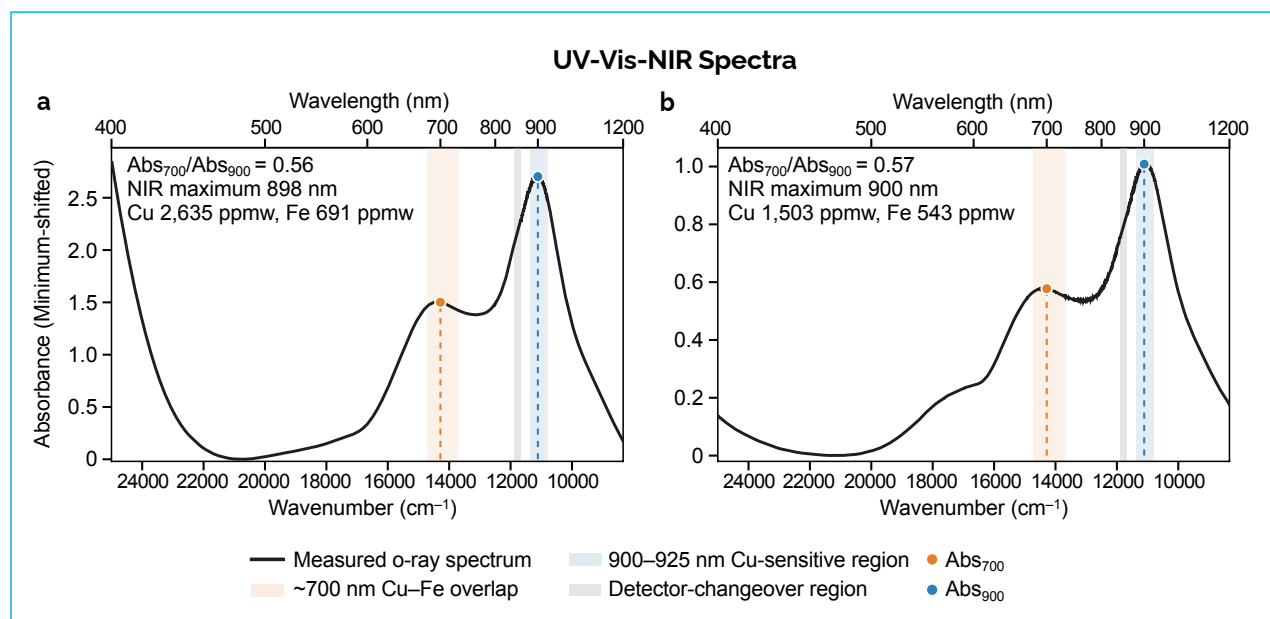


Figure 9: Ordinary-ray (E_{Lc}) UV-Vis-NIR spectra of two Ethiopian Cu-bearing tourmalines—(a) ETH_1 and (b) ETH_14—are shown as minimum-shifted absorbance on a wavenumber axis (wavelength scale on top). Orange shading marks the ~700 nm Cu–Fe overlap region, and blue shading marks the 900–925 nm Cu-sensitive region. Abs₇₀₀ and Abs₉₀₀ are the absorbance values at 700 and 900 nm, respectively, and the grey band is the excluded detector-changeover region. The near-infrared maximum lies at about 900 nm, the position reported for Cu²⁺. It clearly exceeds the absorbance of the 700 nm maximum in both spectra (Abs₇₀₀/Abs₉₀₀ = 0.56 and 0.57, respectively). The median values of Cu and Fe in each stone are also noted.

nm and one in the near-infrared region at around 900 nm. In Cu-bearing tourmaline, the o-ray Cu²⁺ bands lie at about 695 and 900 nm with an intensity ratio of about 0.5 (Rossman *et al.* 1991), whereas the Fe²⁺-related absorptions lie near 700 and 1110 nm, causing a transmission window at about 900 nm (Mattson & Rossman 1987; Krzemnicki & Wang 2022). The 900 nm region is therefore the Cu-sensitive part of the o-ray spectrum.

Both spectra in Figure 9 are dominated by the near-infrared band; Abs₇₀₀/Abs₉₀₀ is 0.56 for ETH_1 and 0.57 for ETH_14, and the maximum lies at 898 and 900 nm, respectively, at the position reported for Cu²⁺. The 700 nm absorbance, to which both Cu²⁺ and Fe²⁺ contribute, does not exceed the near-infrared one in either spectrum, so there is an absence of the Fe-dominated pattern associated with an indicolite designation. Similar Cu-related absorption was observed in all 14 samples, although the Abs₇₀₀/Abs₉₀₀ relationship was evaluated quantitatively only in spectra within the photometric range (the measurable range of absorbance).

In some samples, the absorbance around 900 nm reached the ceiling of what the spectrophotometer could record faithfully (Sharpe 1984). Spectra measured in that condition showed the near-infrared maximum at a different position, between 941 and 994 nm rather than close to 900 nm (see Figure DD-3). This may be related to the samples or the

instruments, and the exact mechanism requires further study. Only spectra recorded inside the photometric range are interpreted here.

Chemical Composition and Internal Zoning

Tourmaline Species and Main Chromophores.

Major-element site-occupancy calculations from the LA-ICP-TOF-MS data, normalised to Si = 6 atoms per formula unit (apfu), placed all 14 stones in the elbaite–fluor-elbaite series, Na(Li_{1.5}Al_{1.5})Al₆Si₆O₁₈(BO₃)₃(OH)₃(OH,F). In all 83 analyses, the X site was Na-dominant and the Y site was Li–Al-dominant. The median B content was 2.91 apfu (2.74–3.19; compare the stoichiometric value of 3). Because F and OH were not determined, the W site was unconstrained, and the two species (elbaite and fluor-elbaite) could not be differentiated. No Ca-dominant (liddicoatite) compositions were encountered, in contrast to part of the Mozambican production (i.e. from Maraca; Karampelas & Klemm 2010).

Copper exceeded Fe in 82 of the 83 individual spot analyses, which had ranges of 373–26,157 ppmw Cu (0.05–3.27 wt.% CuO) and 2–7,368 ppmw Fe (up to 0.95 wt.% FeO). Manganese ranged from 16 to 4,888 ppmw (up to 0.63 wt.% MnO).

Bismuth-defined Subgroups and Colour Zoning.

The 83 spot analyses from the 14 stones could be

Table II: Summary of the three Bi-defined subgroups.*

Subgroup	Bi tier	Spots	Samples represented	Bi min–max (ppmw)	Bi median (ppmw)
SG1	High	35	ETH_1, 2, 3, 7, 9, 12, 14	3214–15088	8075
SG2	Intermediate	26	ETH_4, 5, 6, 8, 9, 10, 11	280–1272	505
SG3	Low	22	ETH_4, 5, 8, 9, 10, 11, 13	28–105	34

* The subgroups are characterised according to three tiers into which the ranked Bi sequence of the 83 analyses falls, separated by two gaps (1,272–3,214 and 105–280 ppmw) and numbered in order of decreasing Bi. See also Figure 10.

separated into three tiers based on Bi content (see Table II and Figure 10a): Subgroup 1 (SG1) with Bi = 3,214–15,088 ppmw (35 spots on seven stones, mainly near-colourless and blue zones), SG2 with 280–1,272 ppmw (26 spots on seven stones, mainly blue, but also greenish blue, near-colourless and pink-to-purple zones), and SG3 with 28–105 ppmw (22 spots on seven stones, mostly green to greenish blue). Each tier is separated from the next by an empty interval: the lowest Bi value of SG1 is 2.5 times the highest value of SG2, and the lowest of SG2 is 2.7 times the highest of SG3. All analyses of eight stones fell within a single Bi tier. Five samples encompassed both SG2 and SG3 domains, and the zoned rough contained all three tiers (Figure 10b). The analysed traverse of seven spots on ETH_9 crossed near-colourless, pink, purple, blue and green zones, for which Bi decreased monotonically from 4,191 to 50 ppmw

(Figure 10c; Table DD-1). Growth striations were visible in the green and purple zones, but they do not by themselves establish the direction of crystal growth. Because green zones occupied apparent cores in other crystals (ETH_4 and ETH_5), ETH_9 may likewise record growth from the green towards the near-colourless zone (with an accompanying increase in Bi concentration); however, this interpretation remains tentative. The coexistence of different tiers within individual stones is consistent with the development of compositional zoning during crystal growth. Since different Bi tiers can coexist within a single crystal, one analysis spot represents only the sampled zone, and multi-spot analysis is required for stone-level characterisation.

Median Cu increased from 2,589 ppmw in SG1 through 11,883 ppmw in SG2 to 15,833 ppmw in SG3, producing a partial association between subgroup and

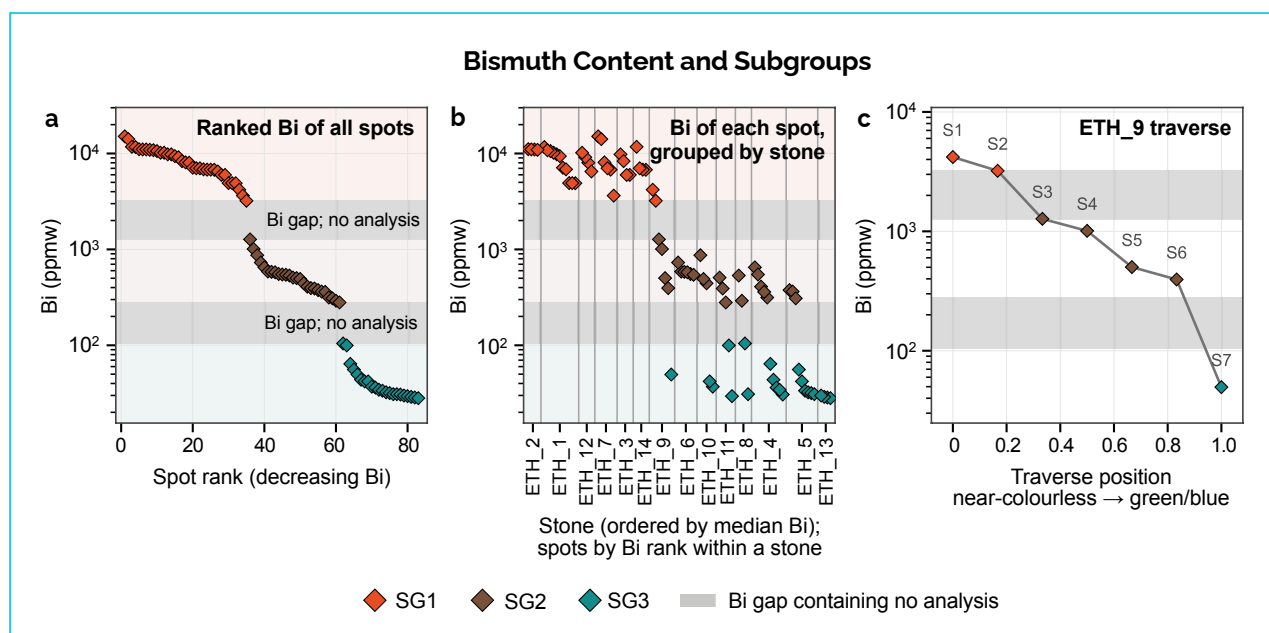


Figure 10: The distribution of the three subgroups (SG1, SG2 and SG3) defined by Bi content is shown within and between stones. Each symbol is one analysis, coloured according to subgroup. The grey bands mark the two empty intervals (in the Bi ranges of 1,272–3,214 ppmw and 105–280 ppmw) that separate the three Bi tiers. (a) A plot of the Bi content of all 83 Ethiopian analyses, ranked from highest to lowest, shows clearly that the Bi tiers are set apart by the two empty intervals. (b) The same analyses, arranged by stone, show the samples ordered by their median Bi content. Eight stones fall entirely within one tier, while the other six contain analyses on both sides of an empty interval, that is, Bi zoning within a single crystal. (c) Bi content along the seven-point traverse of ETH_9, from near-colourless (subgroup SG1) to the green zone (subgroup SG3), shows that this one stone encompasses all three Bi tiers.

colour: all 21 near-colourless to pale-coloured spots and all seven pink-to-purple spots belonged to SG1 or SG2, whereas 18 of the 22 SG3 spots were green to greenish blue. This association is not one-to-one because colour is related to Cu, Mn and Fe. Within SG1 alone, the pale-coloured spots had a median Cu of 2,269 ppmw against 14,173 ppmw for the greenish blue ones, and the single Fe-dominant analysis of the whole set was in a low-Cu pink zone of ETH_7.

Element Correlations. Figure 11a shows Spearman rank correlation coefficients (ρ) for pairs of ten selected elements. Bismuth, Pb and Be were positively correlated with one another, as were Fe, Cu, Mn, Ga and Sn. Correlations between these two sets were generally negative, most strongly for Be–Ga ($\rho = -0.94$), whereas Nd and Zn did not consistently follow either set.

In Figure 11b, the median concentration of each element in each Bi subgroup was divided by the median for all the Ethiopian analyses. The resulting ratios are shown on a logarithmic colour scale, with values above 1 indicating relative enrichment and values below 1 indicating relative depletion. SG1 and SG3 have broadly opposite enrichment patterns. SG2 is not simply intermediate, however, because it shows the greatest relative enrichment in Nd and the strongest depletion in Zn, indicating that the light-REE and Zn concentrations are not tied directly to the Bi tiers.

The correlations in Figure 11a summarise all 83 spots and include both within- and between-subgroup variations, whereas Figure 11b shows relative subgroup enrichment rather than element-to-element correlations. Both diagrams are descriptive and should not be interpreted as evidence of coupled substitutions.

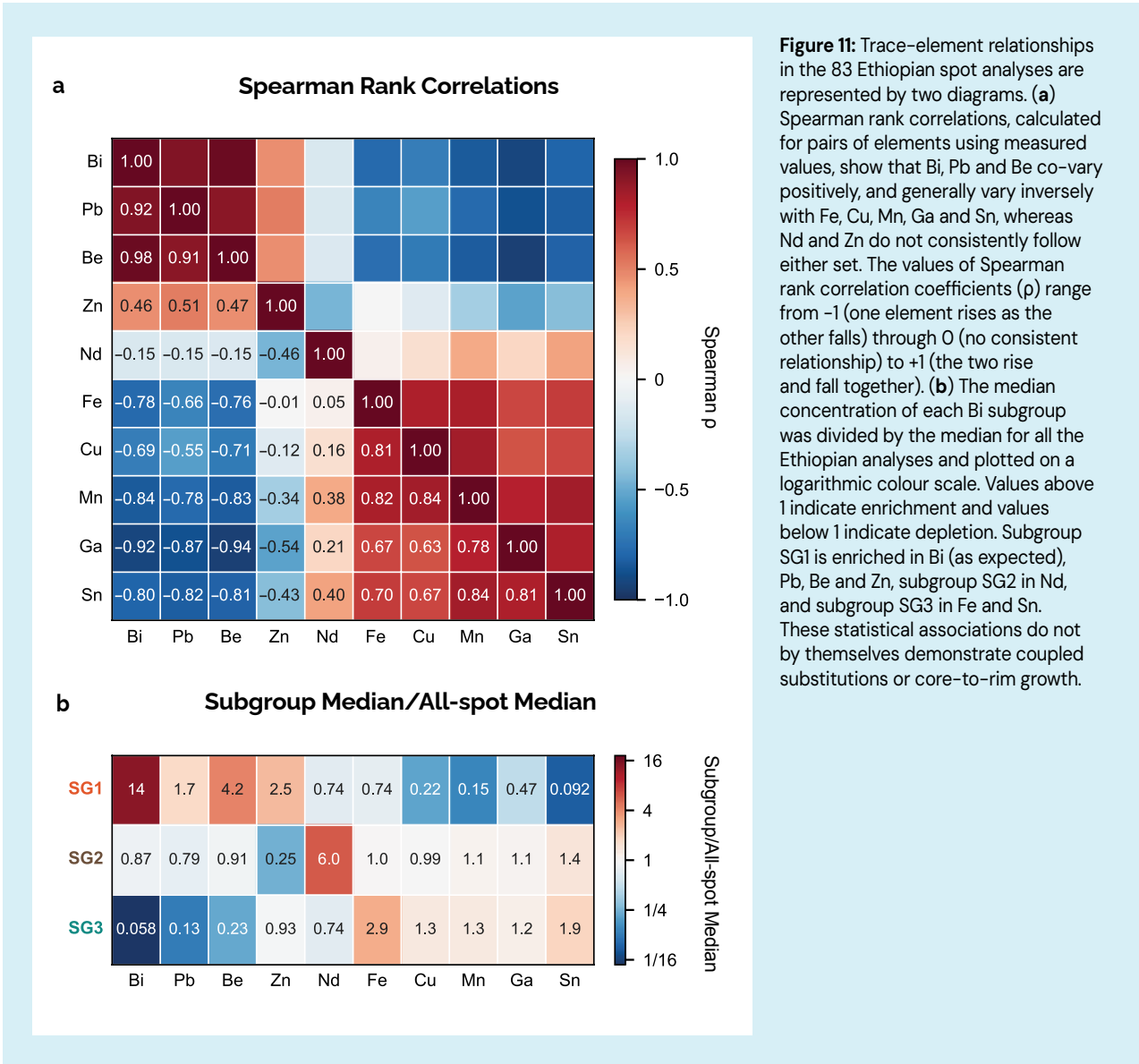


Figure 11: Trace-element relationships in the 83 Ethiopian spot analyses are represented by two diagrams. (a) Spearman rank correlations, calculated for pairs of elements using measured values, show that Bi, Pb and Be co-vary positively, and generally vary inversely with Fe, Cu, Mn, Ga and Sn, whereas Nd and Zn do not consistently follow either set. The values of Spearman rank correlation coefficients (ρ) range from -1 (one element rises as the other falls) through 0 (no consistent relationship) to +1 (the two rise and fall together). (b) The median concentration of each Bi subgroup was divided by the median for all the Ethiopian analyses and plotted on a logarithmic colour scale. Values above 1 indicate enrichment and values below 1 indicate depletion. Subgroup SG1 is enriched in Bi (as expected), Pb, Be and Zn, subgroup SG2 in Nd, and subgroup SG3 in Fe and Sn. These statistical associations do not by themselves demonstrate coupled substitutions or core-to-rim growth.

Geographic Origin Determination

Element Scatter Diagrams. Some conventional two-dimensional scatterplots can successfully separate the Ethiopian material, as shown in Figure 12, in which each spot analysis is plotted individually where both elements were detected.

For V vs Fe (Figure 12a), every Ethiopian analysis lies between 42.9 and 146 ppmw V, whereas the highest single analysis from the other origins reaches 20.3 ppmw V; no analyses from any origin fall in the interval between. Vanadium is the only one of the 57 elements quantified here for which the Ethiopian range does not overlap the range of the other origins. Iron spans 2–7,368 ppmw in the Ethiopian analyses, which is entirely within the range for the other localities, so it is not origin specific.

For Bi vs Pb (Figure 12b), the three Bi-defined tiers appear as separate clusters for the Ethiopian samples, and they are generally displaced towards higher Pb than the other-origin trend at comparable Bi, although some overlap occurs with Nigerian material. This plot also clearly documents the positive correlation between Pb and Bi.

Elevated V in Ethiopian material was previously reported by Emori and Kitawaki (2026) and GIA

(2026), and elevated Ga and Pb by Pardieu *et al.* (2026), Milisenda and Guo (2026) and GIA (2026). Our data agree with regard to V, and for Pb in the Bi-rich SG1 tier. Gallium was likewise elevated, with an Ethiopian median of 631 ppmw vs 272 ppmw for the samples from other origins, but this comparison (not illustrated) did not discriminate on its own: the Ethiopian range of 229–795 ppmw was shared by 972 of the 1,653 analyses from the other origins, most of which were from Mozambique (both Mavuco and Maraca).

Unsupervised t-SNE Visualisation of the Global Locality Dataset. The t-SNE plot for all origins (Figure 13a) shows a clear origin-related distribution of the 1,736 spot analyses from the 483 stones in our dataset, although the degree of separation varies among the previously known sources. Most notably, all 83 Ethiopian spots formed a field that contains no analysis of any sample from another origin. Because t-SNE primarily preserves local neighbourhood relationships, its axes, orientation and inter-cluster distances have no direct compositional meaning. The plot is therefore used to visualise multi-element similarities rather than as a stand-alone method for

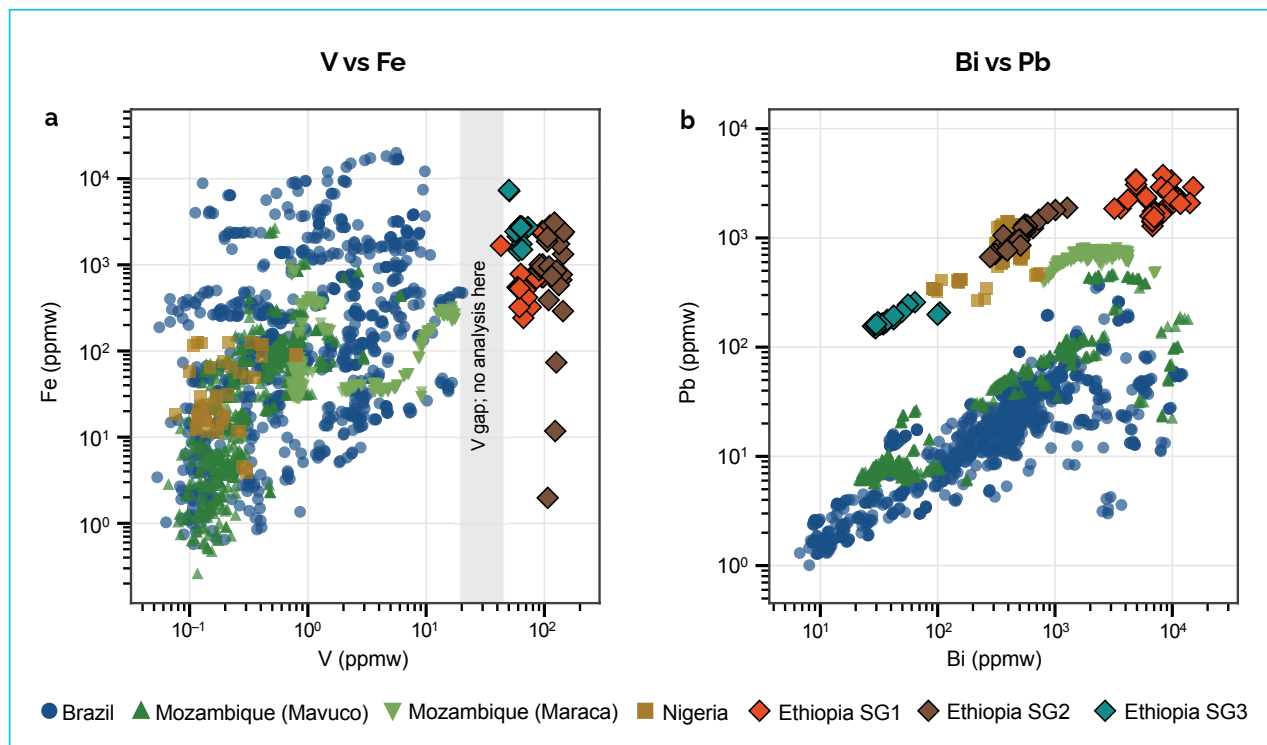


Figure 12: Trace-element diagrams show pairs of significant element concentrations for Cu-bearing tourmalines from Ethiopia and the other origins (Brazil, Mozambique and Nigeria). Each symbol is one analysis (83 Ethiopian analyses for 14 stones and 1,653 analyses for 469 stones from the other origins), and an analysis is plotted only where both elements of the pair are above the limits of detection. Both axes are logarithmic and concentrations are in ppmw. (a) A plot of V vs Fe shows a distinct V gap (shaded) between the Ethiopian and the other-origin analyses. (b) A plot of Bi vs Pb shows the Bi-defined tiers of the Ethiopian samples as three clusters, generally displaced above the other-origin Bi–Pb trend, with some exceptions.

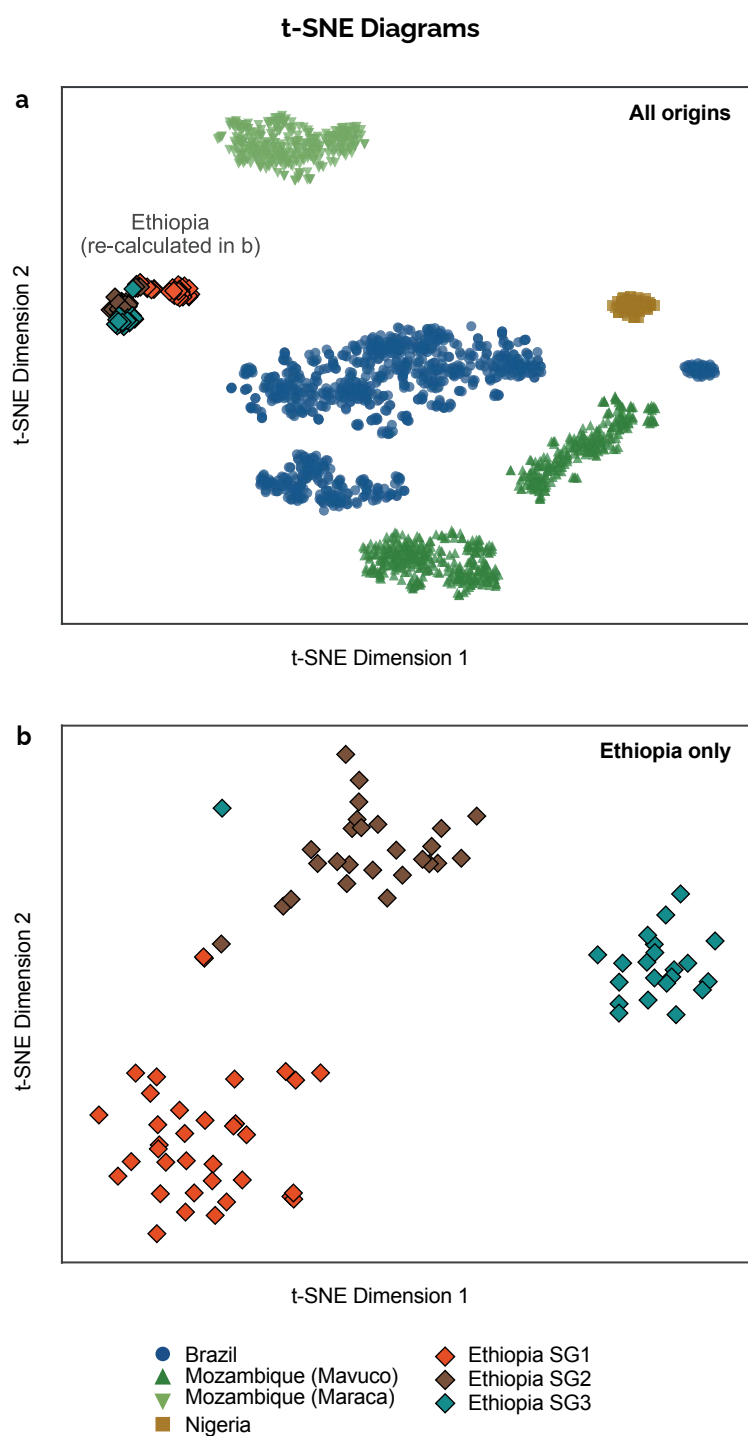


Figure 13: In these results of unsupervised t-SNE visualisation of SSEF's Cu-bearing tourmaline datasets, each symbol is one analysis. **(a)** In the t-SNE plot of the samples from all origins—1,736 analyses from 483 stones in the 57-element space—the 83 Ethiopian analyses form a single group, separate from the samples from the other origins. **(b)** A t-SNE plot calculated for the same 83 analyses of the Ethiopian material alone further resolves the Bi-defined tiers SG1–SG3 as distinct groups. The two plots are from separate calculations, and their axes carry no units, so positions cannot be compared between panels.

determination of geographic origin. The separation of the Ethiopian analyses is also supported by their non-overlapping V concentrations shown in Figure 12a.

When the 83 Ethiopian analyses were recalculated separately (Figure 13b), the internal structure of the

dataset became more apparent. Most analyses form three groupings corresponding to the SG1, SG2 and SG3 subgroups that were defined from Bi concentrations independently of the t-SNE coordinates. Because Bi was included among the 57 elements, the Ethiopia-only plot visualises, but does not independently

validate, the three subgroups. However, the subgroup structure persisted when the calculation was repeated after excluding Bi (not illustrated), indicating that the separation is also carried by covariation among the remaining 56 elements.

REE Systematics and Eu Anomaly. REE patterns normalised to CI chondrite values (McDonough & Sun 1995) are shown in Figure 14. (Most REEs in the Mavuco and Nigerian analyses were below their detection limits, so these two datasets are not plotted in Figure 14a.) Three regimes appear among the Cu-bearing tourmalines (Figure 14a): Brazilian analyses have comparatively low REE abundance (median La $1.1\times$ CI) and negative Eu anomalies (median Eu/Eu* 0.21); Maraca analyses are REE-rich (median La $115\times$ CI) with the most pronounced Eu anomalies (median Eu/Eu* 0.13); and the Ethiopian analyses are moderately light-REE-enriched (La $0.7\text{--}159\times$ CI, median $4.5\times$ CI) with predominantly mild negative Eu anomalies (Eu/Eu* 0.40–1.06, median 0.68).

Within the Ethiopian dataset, REE abundances vary among the Bi-defined subgroups (Figure 14b): SG2 carries by far the highest light-REE contents (median La $35\times$ CI, against $2.2\times$ for SG1 and $3.3\times$ for

SG3), while the Eu anomaly is broadly similar across the tiers (medians 0.71, 0.65 and 0.61).

Heat-treatment Considerations

Among the Ethiopian samples, three faceted stones (ETH_12–14) and two rough samples (ETH_4 and ETH_5) were reported by their suppliers as heat treated. In these, numerous large expansion cracks were observed around fluid inclusions in partially healed fissures. Such cracks also occurred in the non-heated samples, but they were far more numerous in the heated ones and often were oriented perpendicular to the partially healed fissures, whereas in non-heated stones they tended to follow the fissure direction. Because of the relatively low treatment temperature (reportedly below 400°C), heating-related features can be subtle.

In ETH_4 and ETH_5, the pink-to-purple zoning visible in the pre-treatment photographs was no longer visible after supplier-performed heating. Such zoning may therefore support, but does not by itself prove, an unheated status, consistent with observations on Paraíba-type tourmaline from other sources (Fritsch *et al.* 1990).

Epigenetic Fe-rich deposits in hollow channels and fissures were common (Figures 6b and 7a).

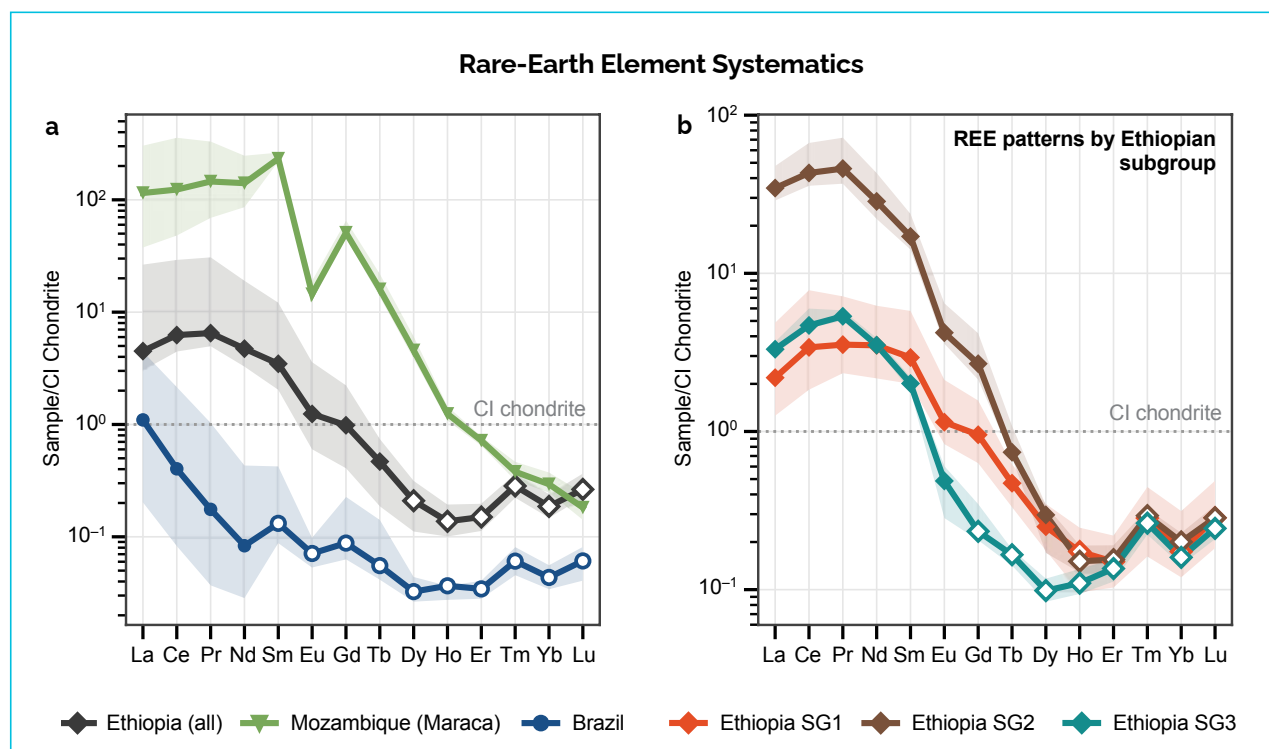


Figure 14: CI-chondrite-normalised REE characteristics of Cu-bearing tourmalines are shown for Ethiopian and other origins. (a) Median (traces and symbols) and interquartile range (shading) show the REE patterns of the Ethiopian samples and of material from Brazil and Maraca, Mozambique. (The REE contents of stones from Nigeria and Mavuco, Mozambique, were largely below detection limits, so these localities are not shown.) (b) The same statistics are shown for the three Bi-defined Ethiopian subgroups. Open symbols mark elements that were below the detection limits in more than half of that group's spots. CI values were taken from McDonough and Sun (1995).

Raman analysis identified hematite in a channel-filling residue from heated sample ETH_4 (Figure DD-2). The appearance of these deposits varied from yellowish brown or orange to darker reddish brown, but their colour and mineralogy were not systematically compared between heated and unheated samples, and therefore are not necessarily diagnostic of heat treatment.

The UV fluorescence and UV-Vis absorption spectra of heated and non-heated samples did not differ significantly and cannot alone establish heat treatment in this material.

Trade Nomenclature and the LMHC Criteria

According to LMHC Information Sheet #6, use of the trade name ‘paraiba’ is independent of geographic origin but is restricted as follows: (1) the stone must be blue, bluish green to greenish blue, green or yellowish green; (2) it must show medium-light to high saturation and tone relative to this tourmaline variety; and (3) its colour must be due mainly to Cu and Mn (LMHC 2023). Consequently, unheated purple or pink Cu-bearing tourmalines fall outside the present LMHC definition (Laurs *et al.* 2008), irrespective of their Cu and Mn contents. This information sheet further excludes stones with low colour saturation containing only traces of Cu, or that fall outside the stated colour range. Hue and saturation are assessed on a finished (cut) stone. The five faceted Ethiopian stones in this study were blue to greenish blue and therefore lie within the colour range (Figure 1), whereas several of the rough samples were strongly colour-zoned and include purple, pink and near-colourless portions (Figure 2). For such material, the designation therefore applies to the resulting cut stone rather than to the rough material. As an example, ETH_1 was a rough piece that included a near-colourless region, whereas ETH_14 was a cut stone. The ordinary-ray spectrum is Cu-dominated in both (Figure 9). These spectra established their cause of colour, but not their trade designation, because hue and saturation are judged on a cut stone, and the proportion of near-colourless material in a rough piece may only become apparent after cutting. In this case, ETH_14 can be designated ‘paraiba tourmaline’, but ETH_1 cannot.

The present data also bear on the third condition: the cause of colour. For all 14 stones, the median Cu concentration exceeded the median Fe concentration; Cu also exceeded Fe in 82 of the 83 individual spot analyses. The single exception was a pink zone in ETH_7—containing 1,488 ppmw Cu and 1,667 ppmw

Fe—but the pink colour falls outside the definition in any case. LMHC Information Sheet #6 also provides an exclusion criterion for Fe-rich Cu-bearing tourmaline: any stone with an ordinary-ray absorbance at 700 nm that exceeds the Cu-related absorbance at 900 nm should not be called ‘paraiba tourmaline’. In the representative ordinary-ray spectra of Figure 9, the 700 nm absorbance does not exceed the near-infrared one ($Abs_{700}/Abs_{900} = 0.56$ and 0.57), so neither spectrum meets this exclusion criterion.

Material reaching the market from the new source in Ethiopia also includes Fe-dominated blue stones better described as indicolite (Milisenda & Guo 2026; Pardieu *et al.* 2026). Because Cu- and Fe-coloured blue tourmalines can be visually similar, the designation cannot rest on appearance alone. Chemical analysis can establish the presence and relative concentrations of Cu and Fe, but for borderline Fe-bearing material the ordinary-ray polarised UV-Vis-NIR spectrum remains the deciding measurement under the LMHC criteria.

CONCLUSIONS

Ethiopian Cu-bearing tourmaline represents an exciting and welcome new addition to the gem trade (e.g. Figure 15). The samples examined for this study belonged to the elbaite–fluor-elbaite series, and all 83 analyses of the 14 samples were Na-dominant at the X site. Microscopically, the samples resembled Cu-bearing tourmaline from other geographic origins. However, pronounced colour zoning involving near-colourless areas was observed in several specimens, which may provide a useful supporting indication of Ethiopian origin when considered with other evidence. A notable compositional feature was the tiered Bi content of our samples: the 83 analyses formed three concentration ranges—SG1 (3,214–15,088 ppmw), SG2 (280–1,272 ppmw) and SG3 (28–105 ppmw)—separated by two blank intervals within this dataset. However, these ranges describe the present sample set and should not yet be regarded as fixed gaps throughout the deposit. Nevertheless, the data establish that Bi can vary over almost three orders of magnitude, with similar levels recurring among stones and coexisting within individual specimens as growth zoning. Lead and Be co-varied positively with Bi, whereas Fe, Cu, Mn, Ga and Sn co-varied inversely with it, indicating a broader compositional gradient for which Bi serves as a convenient index.

For geographic origin determination, elevated V provided the most promising single-element indicator for our dataset, with no overlap between

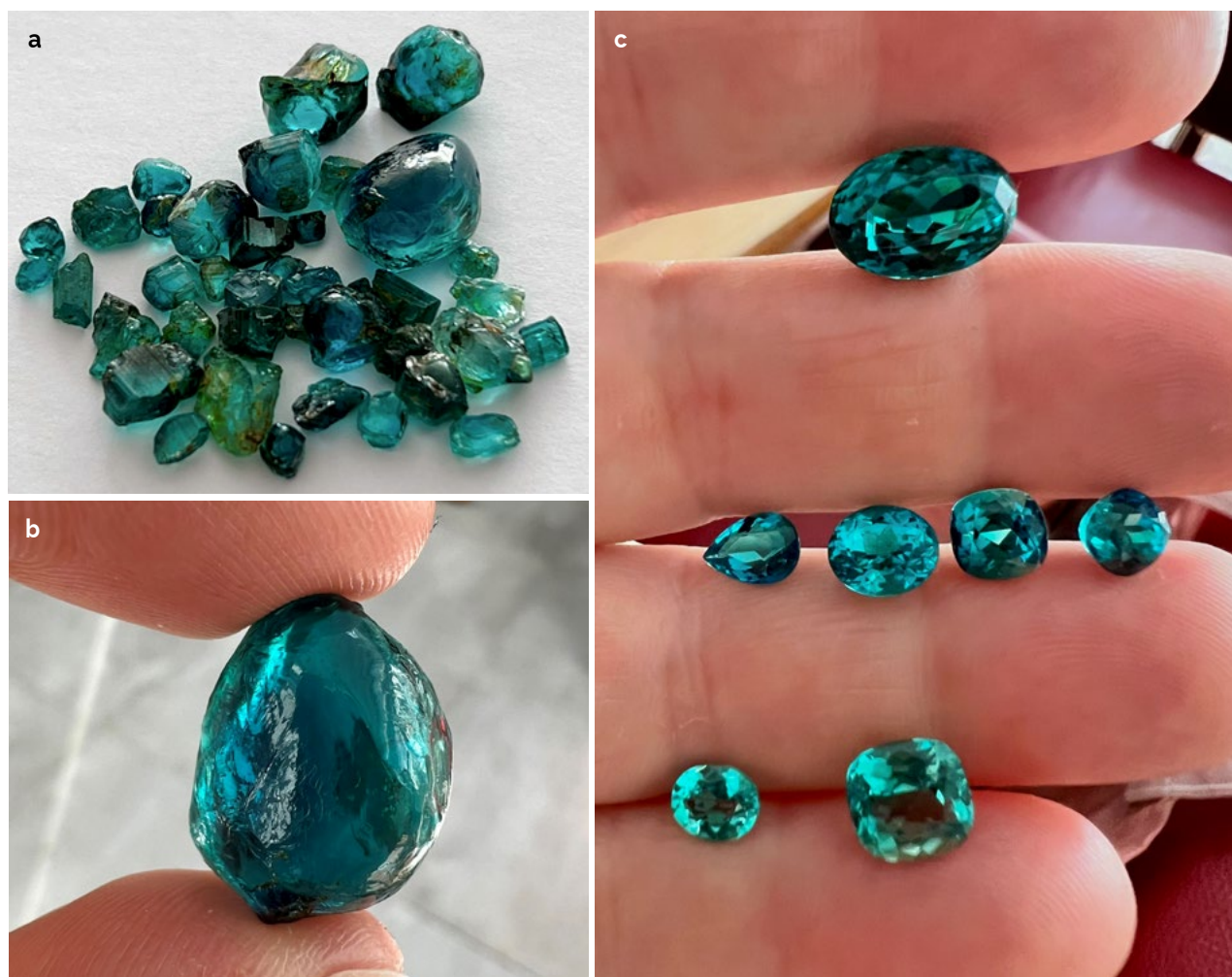


Figure 15: These Ethiopian Cu-bearing tourmalines show attractive blue to greenish blue colouration. The rough material weighs up to 3.76 g (the largest piece in image a is also shown in image b), and the faceted stones range from 0.46 to 4.67 ct. Photos courtesy of Paul Wild GmbH & Co. KG, Kirschweiler, Germany.

the Ethiopian analyses and those from Brazil, Mozambique and Nigeria. Considered together with the multi-element distribution visualised by t-SNE, the light-REE enrichment and the mild negative Eu anomalies, the combination of these chemical factors provided a more robust basis for origin assessment than any single criterion. These observations are based on 14 stones from the first months of production and should be reassessed as the reference

datasets expand.

Because a single analytical spot samples one growth zone rather than the whole stone, multi-spot chemical analysis is necessary for stone-level characterisation. Although blue-to-green stones from the Ethiopian locality may qualify under LMHC guidelines to be traded as ‘paraiba tourmaline’ after cutting, UV-Vis-NIR spectroscopy remains necessary to confirm the role of Cu in the colouration.

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