Karl Schmetzer

Русские Александриты

Russian Alexandrites

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Dr. Karl Schmetzer

with contributions from

George Bosshart
Marina Epelboym
Dr. Lore Kiefert and
Anna-Kathrin Malsy

Alexandrite crystal group of about 8 x 9.5 cm in size, named "miners' fellowship", together with the portrait of Tsar Alexander II as displayed in the Mineralogical Museum at the Urals State Mining University, Ekaterinburg. Alexandrite is regarded as Russia's symbol and the national gemstone of Russia. Photograph by G. Bosshart.

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Figure captions

Front cover: Alexandrite crystal group shown in both daylight and incandescent light; this extraordinary piece was submitted to the Gemmological Laboratory, Liechtenstein for examination in 2009. The sample measures about 8 x 9 cm. Photograph by Th. Hainschwang.

Front inside cover: The first geological map of the emerald and alexandrite mining areas north and south of the Tokovaya River was published by Grewingk in1854, after examining the area during a stay of several months in the summer of 1853.

Back inside cover: Overview of the shaft system of the Troitsky Mine that also shows the different rock types exposed at the surface from exploration and mining activities; after Deev (1911).

Back cover (from left to right):
– Typical growth structures and pleochroism in faceted alexandrite from the Tokovaya area, Urals, Russia. The growth faces represent the pinacoid **a** (100) and the dipyramid **o** (111). Immersion microscopy, polarized light, 35x magnification. Photograph by K. Schmetzer.
– Alexandrite trilling with dipyramidal habit from the Tokovaya area, Urals, Russia. The crystal faces shown are frequently observed in alexandrite from the Malysheva Mine. Crystal drawing and artwork by K. Schmetzer.
– Faceted Russian alexandrite showing colour change from green in daylight to purple in incandescent light; this gemstone of 1.61 ct was obtained from the Rolf Goerlitz Company, Idar-Oberstein, Germany. Photograph by K. Schmetzer.
– Faceted 1.11ct Russian alexandrite and Canadian diamonds set in platinum. By courtesy of Warren F. Boyd of R.T. Boyd Limited, Oakville, Ontario, Canada.

Alexandrite crystals in glimmerite matrix; sample size approximately 9.5 x 19 cm. Mineralogical Museum at the Urals State Mining University, Ekaterinburg. Photograph by G. Bosshart.

Acknowledgements

Content

Emerald and alexandrite crystals have been mined together in the Tokovaya area, Ural Mountains, Russia since the 1830s. The gemstones occur in a massive phlogopite host rock also referred to as glimmerite. The weights of samples are: top left, emerald 435 g; right, alexandrite 97 g; bottom left, emerald 58 g. The photograph is a composite of three separate pictures of different scales. By courtesy of Warren F. Boyd of R. T. Boyd Limited, Oakville, Ontario, Canada.

Introduction

Karl Schmetzer and Lore Kiefert

Except for the Colombian deposits, the mining area of the Urals northwest of the city of Ekaterinburg in Russia is the largest historically known emerald mining field of economic importance in the world. In the fall of 1830 Maksim Stefanovich Kozhevnikov, a peasant of the Beloyarsk district, discovered the first emeralds in the roots of a fallen tree on the banks of the Tokovaya River. Mining and exploration activities began in January 1831 under the guidance of Yakov Vasilevich Kokovin, Director of the Ekaterinburg lapidary works. January 1831 is the date normally quoted by Russian authors for the discovery of the Uralian emerald deposits.[1] Within a period of about ten years numerous emerald occurrences were discovered and subsequently mined.[2]

The mining area, the Izumrudnye Kopi, contains two important emerald-bearing zones termed the Izumrudnye Kopi belt. The main belt strikes north-south for more than 20 km and, at its southern end, intersects a northwest-southeast trending belt of about 8 km in length[3].

The Mariinskoye deposit located in the northern part of the longer belt was discovered in 1833 and initially exploited as the historic Mariinsky Mine.[4] As with many historic mines it was later renamed, circa 1927, the Malysheva Mine. Emerald was mined throughout the early years but after World War II it was a by-product as commercial beryl was exploited for the Russian nuclear programme.

In the communist era Ekaterinburg (Sverdlovsk) was closed to foreigners and very limited information about gem mining in the area has been available. In 1992 Peter Lyckberg managed to visit the area, including the Malysheva Mine, and was informed by his Russian hosts that he was the first foreigner to visit since 1916.[5]

A large quantity of faceted emerald from the Malysheva Mine that had been stockpiled during the communist era came onto the market in 1990, thus permitting a detailed gemmological description of the material.[6] Since 1990, the mine has been operated by a succession of different owners under licenses granted by the Russian government although for several years it was closed completely due to lack of investment.

In July 2005, the Tsar Emerald Corporation, a Canadian company, acquired ownership of the Zelen Kamen (green stone) company that held licences for both the operation of the mine and the export of emeralds. Underground mining at the Malysheva Mine, considered to contain 80% of the known emerald reserves in the Uralian emerald belt, recommenced in 2006 with developments to a depth of about 360 m.[7] However, the mine has been closed since the fall of 2007 because of a licensing dispute with the Russian administration.[8]

Alexandrite, together with emerald, has been recovered from the Malysheva Mine and several other mines and emerald occurrences in the Uralian gemstone belt (Izumrudnye Kopi belt, **Fig. 1.1**). During the summer of 2007, two of the authors (LK and KS) were permitted to

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[1] See Vice-President of Appanage Department (1831).
[2] Von Pott (1842); Emlin (1996); Burlakov et al. (1997).
[3] Grewingk (1854); Fersman (1929); Schmetzer et al. (1991).
[4] For the transcription of names from Russian and German original literature see Appendix.
[5] Personal communication from P. Lyckberg (2009).
[6] Schmetzer et al. (1991).
[7] For details about Malysheva mine ownership and activities see Alferova and Boyd (2007) and "Competent person's report on the Malyshev emerald mine, Sverdlovsk oblast, Russian Federation" (2007).
[8] Personal communication from W. Boyd (2009).

Fig. 1.1 Place-name of the Izumrud (emerald) village en route from Ekaterinburg to the Malysheva (Mariinsky) mining site in the Izumrudnye Kopi emerald belt. Photograph by L. Kiefert in 2007.
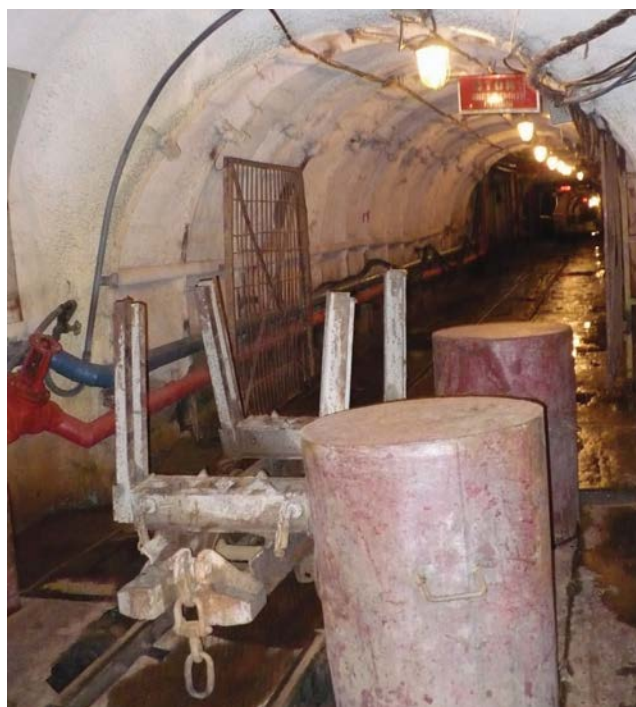
Fig. 1.3 View into the tunnel system at the Malysheva Mine. Photograph by L. Kiefert.

visit the underground workings and examine the exposed micaceous emerald-bearing rock at the Malysheva Mine (**Fig. 1.2 to 1.4**).

Emerald is the main gem produced from the Malysheva Mine (**Fig. 1.5 and 1.6**) with alexandrite as a by-product (**Fig. 1.7**); the ratio of emerald to alexandrite by volume is in the range of about 100:1 to 200:1. The alexandrite is a much sought after gem because of its

Fig. 1.2 a and b Two of the authors (LK and KS) on a visit underground at the Malysheva Mine in 2007.

intense colour change between daylight and incandescent light.

Because of the relative rarity of facetable quality alexandrite, many gemmologists and gem dealers consider it to be as important as diamond, ruby, sapphire and emerald, the big four of the gem world. In 2006 the Tsar Emerald Company requested one of the authors (LK) to issue identification reports for their Russian alexandrites and asked if origin reports were possible on these gemstones. There will always be a demand also for origin reports on exceptional pieces of historical jewellery set with large faceted alexandrites (**Fig. 1.8**).

In recent years there have been many articles and books describing in detail the emerald-alexandrite mines, the history and naming of Russian alexandrite, the morphology and crystallography of historical alexandrite crystals and the chemical and spectroscopic properties of the material.[9] However, compared to emeralds,[10] there is very little data available in gemmological laboratories concerning inclusions, microscopic features and other properties useful for the identification of provenance.

Our examination started with material currently produced from the Malysheva Mine; more information was

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9   Popov et al. (1998); Kozlov (2005); Weinberg (2007); Zhernakov (2009).
10   Schmetzer et al. (1991).
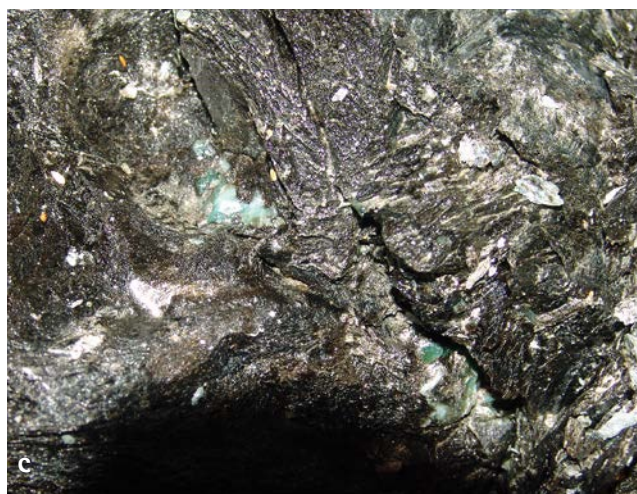
Fig. 1.4 a, b and c (a) and (b) Visitors observing at an emerald producing location at the Malysheva Mine. (c) Emerald in glimmerite host rock. Photographs by L. Kiefert (a and b) and A. Bosshart (c).

added from 19th and 20th century rough and faceted samples from various museum collections and the trade.[11]

The contributing authors examined all the alexandrite samples that were made available. In different chapters of this book they present an overview of the crystallographical, mineralogical and gemmological properties of alexandrite that was unearthed from the Uralian gemstone belt over a period of almost 180 years.

Two chapters are devoted to the history of the emerald mines northwest of Ekaterinburg and to the discovery, naming and use of Russian alexandrite. The connection between two generations of scientists and famous collectors with the Russian emerald and alexandrite mines is shown; the "older" generation including von Wörth, Nordenskiöld, Rose, Maximilian von Leuchtenberg and Perovskii, with the "younger" generation of Koksharov, Kochubei, and Nicolas von Leuchtenberg, followed by Fersman and other Russian scientists in the 20th century.

The last two chapters deal with modern techniques for the description and evaluation of colour and colour change in alexandrites and of modern techniques based on trace element chemistry for origin determination in gemmological laboratories.

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[11] Refer to title figures of chapters 3, 7 and 8, respectively.

Fig. 1.5 a and b Conveyor belts for sorting emerald in the mineral processing plant at the Malysheva Mine. Photographs by L. Kiefert in 2007.
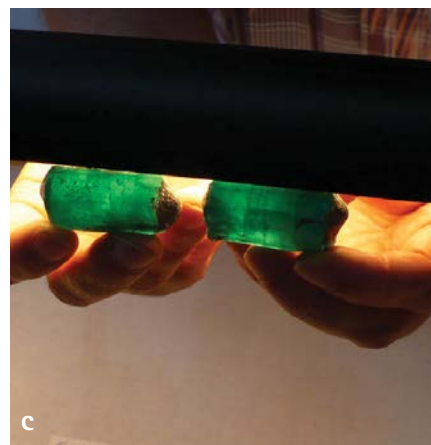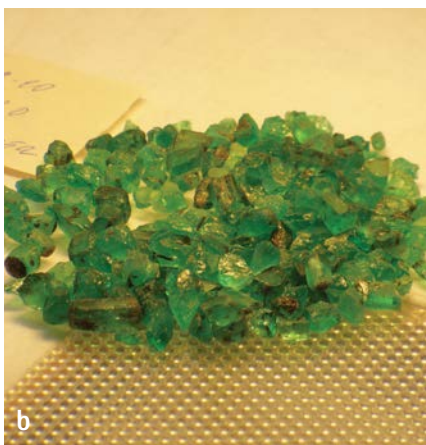
Fig. 1.6 a, b and c Emerald production from the Malysheva Mine. Photographs by L. Kiefert (a and b) and K. Schmetzer (c) in 2007.

Fig. 1.7 a, b and c Alexandrite production from the Malysheva Mine shown in daylight (b) and in incandescent light views (a and c). Size of the small container is approximately 6 x 8 cm. Photographs (2007) by L. Kiefert (a) and G. Bosshart (b and c).

Fig. 1.8 Antique bangle with a centre alexandrite and a diamond cluster surround and shoulders. From the cut of the diamonds and the style of the goldsmith's work, this piece of jewellery is dated between 1870 and 1880. Jewellery of this period is typical of pieces submitted to gemmological laboratories for locality and origin determination of their faceted alexandrites. The 5.9 to 6.0 ct alexandrite from this piece of jewellery was determined as originating from Sri Lanka by the SSEF, Basel, Switzerland. By courtesy of Ernst Färber Company, Munich, Germany. Photograph by C. Merkl.

Emerald crystal group in phlogopite matrix; sample size approximately 7.3 x 8.2 cm. The faceted stone with a weight of 7.19 ct was cut from the rear of the sample. Photograph by J. Scovil, by courtesy from the collection of Peter Lyckberg.

2 The emerald mines in the Tokovaya area – a short historical overview

Marina Epelboym and Karl Schmetzer

Gem minerals such as emerald, alexandrite and phenakite are found in the Ural Mountains, in an area referred to as the Uralian emerald mines (Izumrudnye Kopi belt) that contains the oldest and richest deposits of these stones in Russia. The history of the Uralian emerald mines has been described in numerous papers and books in the Russian language and a detailed presentation of this interesting topic as well as a comprehensive overview were recently published.[1] A short summary of the voluminous book by Semyonov and Timofeev is given in this chapter.

The importance of Russian alexandrite is inseparable from the history of the Uralian emerald mines. In 1830, Maksim Stefanovich Kozhevnikov, working on the shores of the Tokovaya River, found several crystals and chunks of a green stone in the roots of fallen trees. In early 1831 it was established that these green stones were emeralds. In the same year a cutting factory for the emeralds mined in the Beloyarsky Province was established in Ekaterinburg. The head of the factory was Yakov Vasilevich Kokovin who was the first to write about the Uralian emerald mines.[2]

The first area to be prospected was north and south of the Tokovaya River, close to the first emerald find. Eventually three mines, consisting mostly of open pits and surface workings, went into production in this area: Starsky-Troitsky, Tokovsky and Sretensky mines (**Fig. 2.1**). In the following years, prospecting extended further north and south.

In 1833, the Mariinskoye deposit was discovered several miles north of the Starsky Mine and in the following year production commenced as the Mariinsky Mine. During the prospecting work south of Sretensky Mine, a promising area was discovered at the end of 1837 and named Krasnobolotsky (red swamp). Following further prospecting in the area during 1838, serious production started in 1839. This is the area from which the best alexandrites and largest alexandrite crystal groups were found in 1839 and 1840.

Further work around the Krasnobolotsky Mine led to the last of the important discoveries made before the middle of the 19th century. In 1839, a large area northwest of Krasnobolotsky Mine, five kilometres long and one to two kilometres wide, was covered by a series of exploratory holes. The Ostrovnoye deposit was discovered during this work. Despite high expectations of rich deposits, success was limited with very few chrysoberyls and phenakites found. Mine workings were stopped at depths of four to six metres and the miners left. In the same year, 1839, the Chitny deposit south-east of Krasnobolotsky Mine was discovered.

In summary the seven most significant historical mining areas had been discovered before 1840. These include the four mines in the main gemstone belt that runs north-south over a distance of more than 20 km and three mining areas in the second belt running northwest-southeast.[3] The most productive years for emerald production were 1831–1834, 1836, 1839 and 1840. Alexandrite was always regarded as a by-product of emerald production and was not a specific prospecting or mining target.

During 1840, financing for the mines was reduced to twenty percent of previous amounts, all the development work stopped and the miners left the Krasnobolotsky Mine. During an inspection of the mining area in 1853 by C. Grewingk, only one pit in the whole gemstone field was operational and most workings and pits were already flooded. Later in 1853 all mining officially stopped and only an academic interest remained for the mineralogy of the main gem minerals: emerald, alexandrite and phenakite.

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[1]   Semyonov and Timofeev (2005); Zhernakov (2009).
[2]   Kokovin (1831).
[3]   See also Veits (1842).

Geological Map after Fersmann (1929)

Mariinsky mine

Starka

Starsky-Troitsky mine

Tokovsky-Lyublinsky mine

Sretensky mine

Tokovaya

Great Reft

Great Reft

Ostrovnaya

Ostrovnoye mine

Asbestos Mines

Krasnobolotsky mine

Chitny mine

Granite

Gabbro

Porphyrite

Granodiorite

Phlogopite zone with mineralisation

Emerald series

Injected rocks

Serpentinite (altered dunite and pyroxenite)

0   1   2   3 km

◀ **Fig. 2.1** This map of the Tokovaya mining area shows the seven most important historical emerald mines. The Mariinsky, Starsky-Troitsky, Tokovsky-Lyublinsky, and Sretensky mines are located within the northern and central parts of the main belt that runs north–south over a distance of more than 20 km and the Chitny, Krasnobolotsky and Ostrovnoye mines are located within a second belt, approximately 8 km long, that runs northwest–southeast. Artwork by K. Schmetzer, modified from Fersmann (1929).

During this period to 1853, production was under the direct control of two government institutions, namely the Appanage Department and the Imperial Cabinet. From 1831 to 1835 this was under the guidance of Ya.V. Kokovin who was succeeded by I.I. Veits, both of whom also acted as head of the lapidary cutting factory in Ekaterinburg. All stones had to be delivered either to the Appanage Department or to the Imperial Cabinet; stones belonging to the Appanage Department were kept separate from emeralds belonging to the Cabinet.[4] The emeralds were regarded as the private property of the Imperial family. The workers were paid a very small salary plus some commission if they found good stones.

In 1861 the Tsar decided to rent out this land. That year work was done on the most important mines, the Sretensky, Tokovsky, Mariinsky and Krasnobolotsky mines. Further prospecting was done in the Mariinsky and Starsky areas but several attempts to find emeralds in the Krasnobolotsky Mine were unsuccessful. From 1861–1882 the ground was leased to different persons and companies. For example, the mines were on lease to Maria Alexandrovna Trunova between 1863 and 1869 with almost 6000 people working for her in the mines during this period. Between 1878 and 1882, the mines were leased to Alfons Fomich Poklevsky-Kozell (**Fig. 2.2**), a councillor of the State and business man from Ekaterinburg. All work during this period was done with simple hand tools. Working conditions at Krasnobolotsky were worse than at other mines; the proximity to the swamp area resulted in mosquito and black fly swarms and workers had to kindle fires and wear masks.

In 1882 control of the Beloyarsky emerald mines was returned to the cutting factory in Ekaterinburg. South of these mines, at Krasnobolotsky, there were no emeralds found, only alexandrite. From 1883 to 1896 no one applied to lease the land and all work stopped except for a two-year period when local villagers continued to look for emeralds.

In 1897 the Beloyarsky Province emerald mines were leased to Nechaev for 24 years. However, no work was

Fig. 2.2 Portrait of Alfons Fomich Poklevsky-Kozell who leased emerald mines in the Tokovaya region from 1878 to 1882. Photograph by courtesy of W. Boyd.

done and in 1899 Nechaev subleased the mines to the Anglo-French "New Emeralds Company" that, in the same year, made the first new find since the first historic period. They discovered the Makaryevsky Mine, located between the Starsky-Troitsky and Tokovsky mines that was renamed Lyublinsky that year. In April of 1899 they produced emeralds of the same quality as mined in the first historic period. Alexandrites, beryls and aquamarines were also found. This was the first year in the history of the Uralian emerald mines that stones legally appeared in Europe and was followed by the most successful period of emerald mining before the Revolution (**Fig. 2.3**). The company stopped its activities in 1915 and the lease officially ended in 1916.

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[4] See report by Khroshevitskii (1835).

Fig. 2.3 a and b (a) Photograph showing exploration work in a forest area near the Sretensky Mine. (b) Photograph showing washing of emerald-bearing rocks during exploration work in the Tokovaya mining area.
The photographs are undated, but probably date from 1899 to 1916 when most of the mines were leased to the Anglo-French "New Emeralds Company". Photographs published by Fersmann (1929).

In 1917, after the Revolution, nationalization of the cutting factory abolished the rights of the lease holders and the mines became ownerless. During 1918 and 1919, civil war resulted in several ownership changes. In 1919 the mines were nationalized by the Soviet government and from 1923 they were controlled by the "Russkiye Samotsvety" (Russian Gem Trust) that conducted large scale mining for export. In the following years of communist rule the organization and control of the mines changed frequently. Under the Soviet government, most mines officially changed their names in 1927 (**Table 1** and **Fig. 2.4**).

Two new mines were discovered or rediscovered in the 20th century and came into production. Around 1917, Aulsky Mine, situated north of the Mariinsky area, yielded some emeralds as did Starkovsky Mine, southwest of Mariinsky. Several less important emerald occurrences were also found south of the Sretensky area. Additionally, the Cheremshansky Mine, located south of Bolshoy Reft (Great Reft) close to the Krasnobolotsky Mine, located between the northern and southern parts of the historic Uralian emerald mines, became productive. This mine had been found in the early 1830s, but no systematic follow-up work had occurred. The initial development of this mine was done between 1926 and 1929 and the official opening was in 1930.

During the period between 1931 and 1951 unique deposits of emeralds were used as a main source of beryllium for metallurgical applications and, after 1945, the mines mainly produced beryl for nuclear power plants and emerald was not used as a gemstone. After 1945, only four mines were worked for beryl and emerald: the Aulsky (beryl), Malysheva (beryl), Cheremshansky (emerald) and Krasnoarmeisky (molybdenum and beryl) mines. In addition, the whole area was exploited for different rare earths and heavy metals such as molybdenum and tungsten. At Krasnoarmeisky (previously the Chitny Mine) an extraction factory for the enrichment of molybdenum was established in 1941. In 1942 the name of the whole area changed from "emerald mines" (Izumrudnye Kopi) to State Mine Industrial Complex Number 3; they had become part of the State Mine Industrial Complex. In 1951, all emerald mines except Malysheva were closed.

In 1955, the extraction of beryl and emerald continued from the Malysheva Mine to supply material for a new technological process constructed for the enrichment of beryl and a new factory was built in 1957 (**Fig. 2.5**). Underground development at the Malysheva Mine, conducted from 1965, reached depths not achieved at any other deposit. With the discovery of new beryllium deposits made elsewhere in the early 1970s,
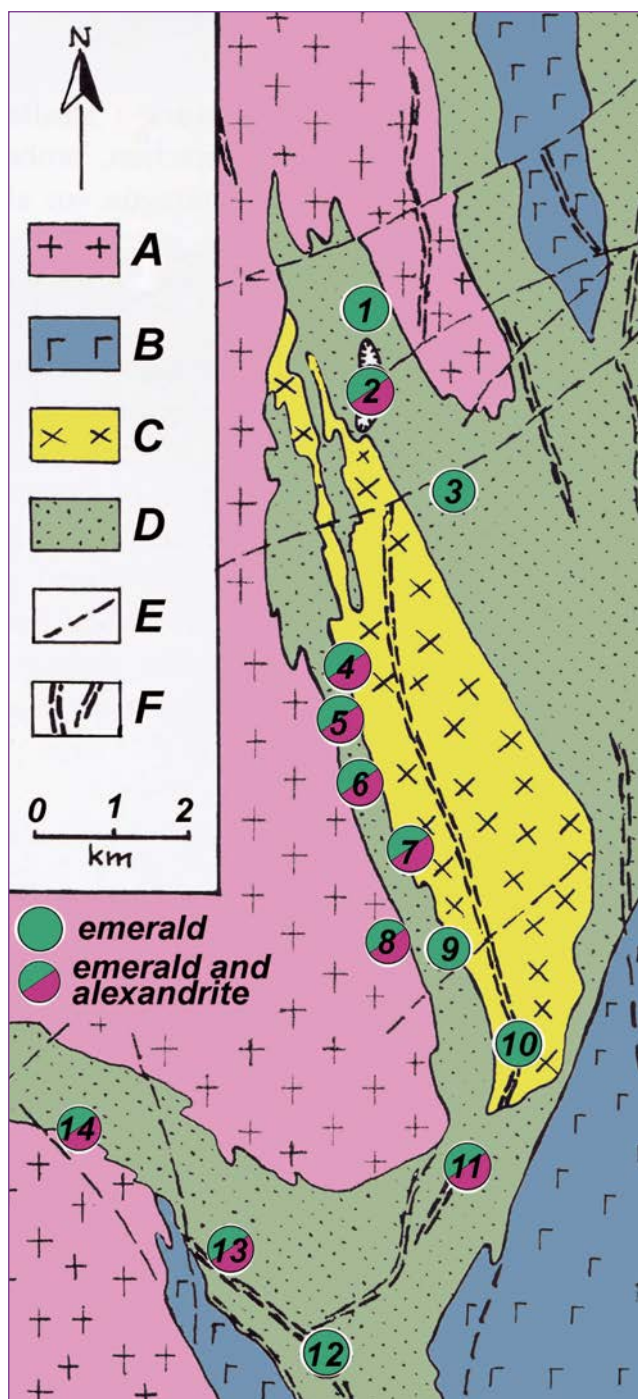
Fig. 2.4 Map showing various localities in the Tokovaya area that were mined from 1831 for emerald, with alexandrite and phenakite as by-products. A general overview is given by Fersmann (1929) and Popov et al. (1998). Map was modified after Burlakov et al. (1997) with additional information taken from Fersmann (1929), Laskovenkov and Zhernakov (1995), Emlin (1996), Popov et al. (1998), Kupriyanova (2002), Kievlenko (2003), and Kozlov (2005).

A granites, granite pegmatites and granite gneisses; B gabbros, metagabbros, dunites, peridotites, serpentinites; C diorites, diorite porphyrites, granodiorites; D amphibolites, quartzites, carbonaceous siliceous schists, talc serpentinites, talc chlorite rocks; E faults; F shear zones.

The mines are: 1. Aulsky, 2. Malysheva, 3. Starkovsky, 4. Pervomaisky, 5. Artema, 6. Krupskoy, 7. Sverdlovsky, 8, 9 and 10 marking less important pits or veins, 11. Cheremshansky, 12. Krasnoarmeisky, 13. Krasnobolotsky and 14. Ostrovnoye. Historical names used before 1927 are shown in Table 1 and Fig. 2.1. Artwork by K. Schmetzer.

mining gradually shifted from the production of beryllium ore back to the production of gem quality emerald. The period between 1970 and 1980 became the renaissance of the Uralian emerald mines (**Fig. 2.6**).

In 1975, a new emerald extraction factory was built incorporating the most modern technology and the extraction rate per volume doubled. In 1990 large quantities of stockpiled emeralds came onto the market and, in the same year, the mines changed completely and only produced gemstones. The Uralian emerald now became a potential participant in the world emerald market and, in 1990, a Russian-Israeli company "Emural" was founded in Moscow for the extraction and cutting of modern emeralds. Emeralds from the Urals were exhibited at the Tucson mineral show for the first time.

In 1995 a group of investors tried to reopen the famous Sretensky Mine, where a number of large historical emeralds had been found. Open pit mining was performed on a large scale (**Fig. 2.7**), but no emeralds of good quality were discovered and work stopped in 1996.

Fig. 2.5 Open pit mining was performed on a large scale at the Malysheva Mine (formerly the Mariinsky Mine) over a period of almost 140 years. The length of the open pit reached 1400 m with a depth between 115 and 125 m. Photograph by K. Schmetzer in 2007.

Fig. 2.6 a, b and c Underground mining at the Malysheva Mine replaced open pit mining in the mid–1960s. These views of underground working scenes date from the 1970s or 1980s. Photographs by courtesy of W. Boyd.

Fig. 2.7 a and b In 1995, a group of investors attempted to reopen the famous Sretensky Mine where some of the best quality and largest emeralds had been found in the 19th century. Although open pit mining was performed on a large scale, work stopped in 1996 because no emeralds of high quality had been discovered. Photographs by P. Lyckberg.

In 1995 mining at the Malysheva Mine by "Emural" stopped because of various problems. The next 10 years were characterized by frequent changes of ownership and/or mining rights between different groups of investors and share holders. However, due to the lack of investment, production was limited during this period.[5]

The major companies involved in this period were "Izumrudnye Kopi Urala" (Ural Emerald Mines), Norfin and "Zelen Kamen" (green stone). In 2005, mining rights of Malysheva emerald mine as well as export licences for emerald and alexandrite were transferred to the Canadian "Tsar Emerald Corporation" and/or their Russian subsidiary.[6,7] The mine closed in the fall of 2007.

Over the years the emerald mines have had a complicated history. However, even when mining ceased for a few years, there was always someone ready to pick up the work again. Clearly these precious stones will continue to be a source of interest and great value for generations to come.

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[5] Production figures for rough, cleaned alexandrite (without admixtures of mica and other minerals) are available for an almost four-year period from 2001-2004, when Malysheva Mine was worked, at least partly, by the "Izumrudnye Kopi Urala" (Ural Emerald Mines) company. The total production of facetable material was 9,167 grams, which were classified and subdivided according to the following table (courtesy of Vitalii Repei, personal communication 2010):

Colour change	Clarity and size							
	Clean, above 10 mm		Clean, 2–10 mm		Moderately included, above 10 mm		Moderately included, 2–10 mm	
Fine	0.29 %	27 g	0.36 %	33 g	1.60 %	147 g	1.77 %	162 g
Medium	0.44 %	40 g	1.33 %	122 g	8.19 %	751 g	10.06 %	922 g
Fair	0.47 %	43 g	4.71 %	432 g	21.51 %	1972 g	49.26 %	4516 g
Sum	1.20 %	110 g	6.40 %	587 g	31.31 %	2870 g	61.09 %	5600 g

It is concluded that larger clean (gem quality, facet grade) samples with good colour change were extremely rare.

[6] For details about Malysheva Mine ownership and activities see Alferova and Boyd (2007) and "Competent person's report on the Malyshev emerald mine, Sverdlovsk oblast, Russian Federation" (2007).

[7] See also chapter 1; a detailed history of Malysheva Mine since 1990 including production figures for emerald and alexandrite for different years is available from "Competent person's report on the Malyshev emerald mine, Sverdlovsk oblast, Russian Federation" (2007).

a

b

Alexandrite crystal group and antique ring with faceted alexandrite, Naturhistorisches Museum, Vienna, Austria. The faceted Russian alexandrite (No. F 9122) weighs 12.8 ct, the sample was purchased in 1890. The crystal group (No. A. f. 484) was purchased in 1842 and measures about 7 x 7 cm with the size of the crystals varying from 3.5 to 5 cm.
The same crystal group shown in different orientations (a) in incandescent light. Photograph copyright Naturhistorisches Museum, Vienna, Austria, reproduced by permission. (b) In day-light. Photographs by K. Schmetzer.

Discovery, naming and historical use of Russian alexandrite

Karl Schmetzer

Alexandrite can almost be called the national gemstone of Russia[1] and until recently, the identification of the first alexandrite crystals was not attributed to a particular person. In the 19th century, the great prestige of alexandrite was based on two facts: its name, in honour of the Tsarevich,[2] the future Tsar Alexander II, and its colours, green in daylight and red in incandescent light, represented the national military colours of Imperial Russia.

3.1 The first mineralogical descriptions of alexandrite

The first details of the discovery of alexandrite are reported in a book describing the scientific activities of the Russian Imperial Mineralogical Society entitled "Schriften der Russisch-Kaiserlichen Gesellschaft für die Gesammte Mineralogie".[3] This book, a special 25th anniversary volume of the Russian Imperial Mineralogical Society, was edited by H. A. G. von Pott, the first Secretary of that Society. It records that in 1833 Count L.A. Perovskii, at that time Vice-President of the Appanage Department, submitted four samples from the Uralian emerald mines to the Society in Saint Petersburg for investigation.

It is further stated that these crystals were identified as chrysoberyl by Franz von Wörth as a result of the measurement of crystal angles and blowpipe examination (**Fig. 3.1**). Additional samples submitted to von Wörth in 1834 confirmed the first identification. Perovskii also mentioned a "special dichroism" that led to the discovery of colour change in daylight and incandescent light.

It is recorded also that Nils von Nordenskiöld made the same observations and concluded that the mineral "deserves the first rank among the gemstones" because of these particular optical properties. He suggested naming the colour-change gem variety of chrysoberyl as ALEXANDRITE in honour of the Tsarevich Alexander Nikolaevich (see **Fig. 3.30**), the future Tsar Alexander II

Fig. 3.1 Portrait of Franz Iwanowitsch von Wörth (1786–1856). Wörth was one of the founding members of the Russian Imperial Mineralogical Society (established in 1817) and served as their second Secretary until 1856. He examined the first crystal fragments of the new mineral from the Uralian emerald mines that was later named alexandrite. Lithograph by courtesy of the Russian Mineralogical Society.

(reigning from 1855 to 1881), who celebrated his coming of age on the day the mineral was discovered in Urals.[4]

However three years previously (1839), the first detailed mineralogical and crystallographic description of Uralian alexandrite had already been published by

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[1] "Alexandrite is believed to be Russia's symbol"; Kozlov (2005).
[2] Crown Prince.
[3] Edited by von Pott (1842c) in German, meaning the "Russian Imperial Society for the Complete Mineralogy".
[4] In the Russian Empire the older Julian calendar was used until 1917, this differs from the Gregorian calendar used in Western Europe by 12 days. In parts of the original documents cited such as in most of the letters from Count Perovskii to Nordenskiöld, both dates are given. However in many other historical documents, letters or 19th century references, it is not always clear as to which calendar the dates refer. Thus, in order to avoid confusion and if not conclusive in its context, the author sometimes only quotes the month of an historical event.

Fig. 3.2 Portrait of Gustav Rose (1798–1873). Rose became professor of mineralogy at Berlin University in 1826. Together with Christian Gottfried Ehrenberg, he accompanied Alexander von Humboldt on research explorations to the Urals, the Altai and the Caspian Sea (1829). Investigations based on crystal morphology and chemistry led to the discovery of several new minerals from the Ural Mountains. For example, he first described perovskite (1839a). In another paper of the same year, he published the first mineralogical descriptions and crystal morphology of the colour-change chrysoberyl trillings from the Urals (Rose, 1839b). This chrysoberyl variety was later named alexandrite in 1842. Lithograph from Rohrbach after a drawing of Paul Bürde, circa 1829. By courtesy of Museum für Naturkunde, Mineralogical Collection, Humboldt University Berlin and reproduced with permission.

Fig. 3.3 a and b Alexandrite crystals from the Tokovaya area, Urals, Russia. (a) The first drawing of a cyclic twin (trilling) was published by Rose (1839b) after crystallographic studies of the first samples he obtained in Berlin. (b) The first (theoretical) drawing of a single crystal was published by Rose (1839b) after crystallographic studies of several trillings. An actual single crystal was not available to him at the time and the occurrence of single crystals still remains very rare.

Gustav Rose (**Fig. 3.2**) in Poggendorff's Annalen der Physik and Chemie,[5] at that time a leading journal of science. This was also reported in a supplement to the second volume of the description of his Russian expedition with A. von Humboldt and G. Ehrenberg in 1829.[6] Rose was unaware of the name given in honour of the future Tsar Alexander II and in both publications he described the mineral as chrysoberyl and not alexandrite. However Rose had already determined the chromium content of the samples and described the mineral as a potential new gemstone, although the samples made available to him by Perovskii were only translucent and heavily fractured.

Rose published the first crystal drawings of pseudohexagonal twins (**Fig. 3.3 a**) consisting of three individuals and also the morphology of a theoretical single crystal (**Fig. 3.3 b**); a real untwinned single crystal was not available to him. He described the main crystal forms as **a** {100}, **b** {010}, **o** {111} and **n** {121} and mentions crystals with re-entrant angles formed by the faces **n** or by a combination of **n** and **b**. When the faces **n** and **b** are small, almost no re-entrant angles are seen. Furthermore, Rose described the colour change between daylight and incandescent light.

In the Berlin collection, several historic alexandrites from the Urals still have the original labels handwritten by Rose (**Fig. 3.4**), but it is not documented which samples he used for his investigations. Some representative alexandrites that were documented as being presented to Rose by the Saint Petersburg Mining Institute[7] do not record the year in which they came into the Berlin collection.

The first quantitative chemical analysis of chrysoberyl from the Urals, including both colour-causing trace elements iron and chromium, was published in 1842.[8] The author was a member of the Russian Mining Engineer Corps working in Heinrich Rose's (a brother of Gustav Rose) laboratory at Berlin University. He analysed two different samples of chrysoberyl, one from Brazil and one from the Urals, but did not use the designation alexandrite in his paper.

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5   Rose (1839b).
6   "Reise nach dem Ural, dem Altai und dem kaspischen Meere", Rose (1842).
7   Refer to title figure of chapter 9.
8   Awdejew (1842).

Fig. 3.4 The collection of the Museum für Naturkunde, Berlin, hosts several alexandrite crystals with original labels written by Gustav Rose. The sample pictured measures about 1.5 x 1.5 cm. It was not possible to identify the actual alexandrites that were examined by Rose in his first studies of their crystal morphology as published in 1839. Photograph by K. Schmetzer.

Fig. 3.5 This book entitled "Schriften der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie", was published in 1842 by the Russian Imperial Mineralogical Society, the volume summarizes activities of the Society from 1817 to 1842. The book contains a ten page summary of the mineralogical properties of chrysoberyl from the Urals and the first details of the naming of this gem variety in honour of the Tsarevich, the future Tsar Alexander II. Photograph by P. Reith.

Consequently, to this author's knowledge, the name alexandrite was first published in the "Schriften der Russisch-Kaiserlichen Gesellschaft für die Gesammte Mineralogie", edited by von Pott and was not previously generally known or used. This book (**Fig. 3.5**) describes various activities in the fields of mineralogy, geology and palaeontology between 1817 and 1842. In the chapters dealing with emeralds from the Urals,[9] two extraordinary samples belonging to the Cabinet of Tsar Nicolas are mentioned. The first sample, made up of a group of emerald crystals in matrix, is probably the specimen kept at the Mineralogische Staatssammlung, Munich. The second sample is a crystal that, together with its micaceous matrix, weighs about 2226 grams and is now preserved at the Fersman Museum, Moscow. We will follow the history of these two extraordinary samples later in this chapter.[10]

Pages 116 to 126 of the 1842 book mentioned above are dedicated to the first description of Uralian chrysoberyl that was named alexandrite in honour of the Tsarevich (**Fig. 3.6**). The mineral normally occurs as single crystals in mica schist, but it is mentioned that several larger crystal groups were in the collection of Perovskii.

Specifically, the chemical examination of the mineral performed by von Wörth using blowpipe techniques[11] is reported and chromium is mentioned as the colour-causing trace element. The crystal morphology and twinning determined by Rose is reproduced, including his crystal drawings. The colour change from green in daylight to purple or violet in incandescent light, especially when viewed by candle light in the dark, is quoted. A slice cut from an alexandrite trilling, examined by von Lenz using polarized light, is described in great detail.

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[9]   Von Pott (1842b).

[10]   See sections 3.3.1 and 3.3.3, respectively.

[11]   A standard chemical examination at that time; see, e.g., Berzelius (1828).

Fig. 3.6 a and b The 1842 volume of the Russian Imperial Mineralogical Society contains two drawings of an alexandrite crystal group in both (a) daylight and (b) incandescent light. However the sample orientations are different. The alexandrite drawings were prepared by Franz von Wörth and lithographed by J.P. Hubert. In the hand coloured plate a more natural appearance for the crystal group was achieved by gluing on minute mica flakes. Photographs by P. Reith.

Following the extended description of this extraordinary dichroism,[12] it is only briefly mentioned in the 1842 book that von Nordenskiöld determined identical physical and chemical properties. Because of the colour change, transparent crystals of this mineral were described as being comparable to gemstones of the first rank and Nordenskiöld suggested the name ALEXANDRITE for this chrysoberyl variety. Finally, it is reported that Veits, Director of the Ekaterinburg lapidary works and successor to Kokovin, discovered another occurrence of alexandrite in 1839. From the approximate locality given, this occurrence is one of the mines located in the southern northwest to southeast-striking gemstone belt. It is mentioned[13] that the Ostrovnoye deposit was discovered by Veits which fits the 1842 description.

Nordenskiöld first visited the Urals in 1849[14] and it has always been a matter of speculation as to where he obtained the alexandrite samples that were used in his work and whether an original paper by him exists on this subject. This information is not given in the 1842 book. The author (KS) recently found a short note from 1835[15] which clarifies the first point. Brewster (**Fig. 3.7**) described a new mineral that was "supposed to be a variety of cymophane" (**Fig. 3.8**), a synonym used at the time for chrysoberyl. Brewster received one sample of this material from Nordenskiöld, whom he had known since the early 1820s.[16] The draft of a letter from Nordenskiöld to Brewster,[17] written in December 1834, confirms a statement by Brewster that several specimens were given to Nordenskiöld from Perovskii in the spring of 1834. Brewster had already referred to the colour change of his sample and described the chrysoberyl (cymophane) as consisting of three single crystals united at angles of 60°. To the author's knowledge, this is the first note in a

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[12] What we would call now pleochroism in daylight and incandescent light and its relation to colour change; for more details see also Haidinger (1847, 1849).
[13] Semyonov and Timofeev (2005).
[14] Eichwald (1870); Golynskaya and Svirina (1997).
[15] Brewster (1835).
[16] Eichwald (1870); Golynskaya and Svirina (1997).
[17] See section 3.2.

Fig. 3.7 Portrait of Sir David Brewster (1781–1868). Brewster was based in Edinburgh, Scotland for most of his working life and devoted an important part of his scientific researches to various problems concerning optics. He was also an active editor of various scientific journals. In December 1834, he was consulted by Nils von Nordenskiöld about the cause of colour change in a newly discovered variety of chrysoberyl from the Urals and one crystal was submitted to him for research. After a short period, Brewster published the preliminary description of the new material in February 1835. This is now regarded as the first scientific publication of alexandrite. Photograph circa 1860, Hulton Deutsch Collection/Corbis.

Sir David Brewster's *Notice of a new Mineral.* 133

XXI. *Notice of the Optical Properties of a new Mineral supposed to be a Variety of Cymophane. By* Sir David Brewster, K.H., F.R.S.

HAVING just received from my friend Mr. Nils Nordenskiold of Helsingfors, a specimen of a new mineral having interesting optical properties, I hasten to communicate a brief notice of these to the readers of this Journal.

Mr. Nordenskiold received specimens of this mineral last spring from His Excellency Sir L. Peroffsky of St. Petersburgh. It was found in the Emerald mines near Caterinenburg in Siberia; and it occurs in large crystals from one to two inches in diameter, which are generally composed in the same manner as is shown in fig. 38, plate vii., of the second volume of Mohs's Mineralogy. Mr. Hartwall is at present engaged in analysing the mineral, the result of which we shall communicate as soon as it reaches us. Mr. Nordenskiold, however, has ascertained that its colouring matter depends on a small admixture of *oxide of chromium.*

When this mineral is seen in daylight it is of a bright *green* colour, whereas by candlelight its colour is a *pink red.* Mr. Nordenskiold has likewise observed, that when a compound crystal is examined with a piece of tourmaline, or in polarized light, one portion of it is of an *emerald green* colour, while another is of a *faint dirty yellow* colour; and that when the crystal is turned round 60°, the part which was *yellow* becomes *emerald green,* and *vice versâ.* Mr. Nordenskiold adds that the mineral seems to be more transparent in candle- than in daylight.

Having repeated these experiments I have found them in every respect perfectly correct; the *yellow* colour, however, which is described as dirty, loses this character when the specimen is placed in a fluid, and it then appears to be intermixed with *red,* so as to show that if the thickness of the specimen were successively increased, the colour would be *redder* and *redder,* and terminate in a *bright red* tint.

Although Mr. Nordenskiold has mentioned that the compound crystals resemble the starlike compound crystals of *carbonate of lead* figured by Mr. Haidinger in his edition of Mohs's Mineralogy, yet, from the optical phænomena, we are disposed to regard the compound as consisting of three single crystals united at angles of 60°, for if the united crystals were each compound, the colours would change at every 30° of revolution.

134 Prof. Forbes *on the Refraction and Polarization of Heat.*

The change of colour which is exhibited by looking through the mineral in *day-* and in *candle*-light, arises from two causes: 1st, from there being an *excess* of *red* and a *defect* of *blue* rays in the light of a candle compared with the light of day; and 2ndly, from the substance employed having a greater disposition to transmit one kind of rays in preference to another, or, what is the same thing, being more transparent for one kind of rays than for another kind, when their intensity is the same.

In the present mineral its colour is *green*; but when we analyse it with the prism we find that the *green* is a compound colour consisting of red and green, the *green* predominating greatly in *daylight*: but in *candle*light the colour is a *pink red,* because the *greater* quantity of *red* in this light and the *smaller* quantity of blue and *green,* gives the *red* colour a decided predominance over the *green,* so as to make the compound colour *pink red.*

There are several crystals, natural and artificial, and various solutions in which this change of colour is beautifully seen. It is particularly visible in the *green* juices of plants, which are *green* in daylight, and of a *blood red* colour in the light of a candle.

In the mineral under our consideration Mr. Nordenskiold found traces of the *oxide of chromium,* to which he attributes its colour. That this is the colouring matter, and that the action of this metal is the cause of its peculiar property in reference to light, may be inferred from the fact that the very same property is possessed by the *triple oxalate of chromium and potash,* and also by the *sulphate of ammonia and chromium,* whether these salts are used in the solid state or in a state of solution.

Fig. 3.8 The first scientific publication by David Brewster on the new colour-change mineral, later named alexandrite. The mineral variety was first described as colour-change cymophane and the article was published in February 1835 in the London and Edinburgh Philosophical Magazine and Journal of Science.

scientific journal about, what was later named, alexandrite. Brewster also noted the chromium content of the samples and observed a similar colour change in certain chromium salts and their solutions. Although this note has been mentioned,[18] it has not been cited in later papers about alexandrite.

It is obvious that von Pott, who is mentioned as editor of the "Schriften der Russisch-Kaiserlichen Gesellschaft für die Gesammte Mineralogie" did not write the various anonymous contributions collected within this volume.

An index in the 1854 volume of the "Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft" covers all publications of the Society from 1830 to 1854. In this, index pages 116 to 126 of the 1842 volume contain the description of alexandrite that is attributed to Lenz, Rose, Veits and Nordenskiöld as authors. This indicates that, neglecting the work of von Wörth, the first description of colour-change chrysoberyl using the name alexandrite was assigned to these four authors. This view was still current in the 20th century.[19]

3.2 Documents from the Nordenskiöld family archive and correspondence with Berzelius

The Nordenskiöld family archive housed at the National Library of Finland, University of Helsinki, contains several thousands of unpublished documents. Following a request by the present author (KS), Mrs. Ilona Fors, one of the staff members of the National Library examined hundreds of documents and selected the following letters belonging to Nils Gustaf von Nordenskiöld (**Fig. 3.9**):

a) two letters from F.I. von Wörth to Nordenskiöld (1831 and 1832, in German)

b) two letters from I.I. Veits to Nordenskiöld (1838 and 1857, in German)

c) three letters from Heinrich Rose to Nordenskiöld (1844, 1845 and 1853, in German); Heinrich Rose was the brother of Gustav Rose, a chemist at Berlin University

d) eleven letters from L.A. Perovskii to Nordenskiöld (1831–1852, ten in French, one in German)

e) one letter from D. Brewster to Nordenskiöld (1825, in English).

She also selected the following drafts of letters to various persons:

a) four drafts of letters from Nordenskiöld to L.A. Perovskii (1838–1853, in French, partly bilingual French/Swedish)

b) one draft of a letter from Nordenskiöld to D. Brewster (1834, in English)

c) two drafts of letters from Nordenskiöld to F.I. von Wörth (one in German, 1837 one in Swedish, undated)
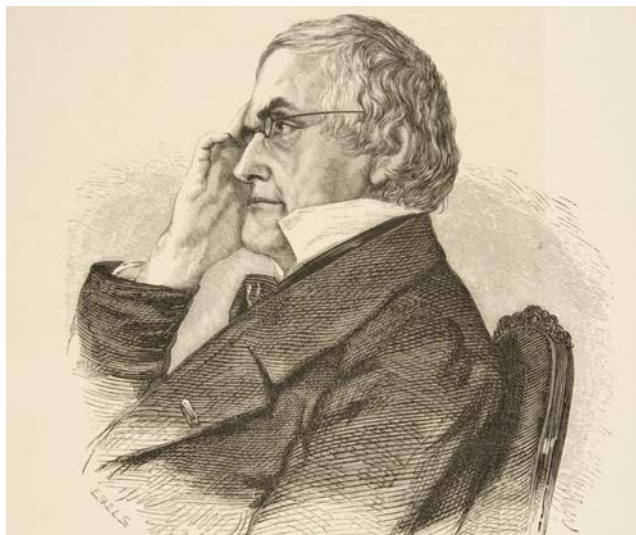
Fig. 3.9 Portrait of Nils Gustaf Nordenskiöld (1792–1866). From 1823 Nordenskiöld was superintendent of mines in Helsingfors (Helsinki), Finland. His work was devoted to the development of the mining industry and study of mineralogy in Finland. He was also in close contact with Count Perovskii from whom he received many interesting mineralogical specimens from Russian localities over a period of more than 20 years. Nordenskiöld first described the beryllium silicate phenakite as a new mineral originating from the emerald fields in the Ural Mountains and he was also involved in the determination of the chromium-bearing colour-change chrysoberyl variety from the Tokovaya area. Portrait work by A. Janke, circa mid-1850s, National Board of Antiquities, Archives for Prints and Photographs, Helsinki, Finland.

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[18] In detail by Poggendorff (1835), and also briefly by Berzelius (1837).
[19] Laitakari (1934).

d) one draft of a letter from Nordenskiöld to A. Kämmerer (1837, in German); Kämmerer was a pharmacist and a member of a group of mineral collectors in Saint Petersburg

e) eight drafts of letters from Nordenskiöld to J. Berzelius (1832–1838, in Swedish); Professor Berzelius was one of the most famous chemists of the first part of 19th century, Nordenskiöld worked in his laboratory in Stockholm for about one year during 1819.[20]

In general, there is no gap in the 1820s, 1830s and 1850s, but the archive contains a smaller number of letters from the 1840s than the decades before and after.[21]

The letters from von Wörth, Veits and Rose were between colleagues or close friends dealing with mineralogical problems, the exchange of research samples and with economic mineralogy but did not mention the alexandrite discovery. The drafts of letters to von Wörth and Kämmerer are of the same type.

Most of the letters from Perovskii (**Fig. 3.10**) document the intense cooperation between him and Nordenskiöld during the whole period under consideration. They deal with the submission of numerous research samples from Perovskii's collection and/or from the Uralian emerald mines. Some of the "unknown" samples mentioned are difficult to identify, because Nordenskiöld's replies to Perovskii are not available. Two letters, dated April 1833 and May (?) 1833, contain details of their cooperation in the discovery and description of phenakite as a new mineral from the Uralian emerald mines.

Two fragments of another unknown mineral were sent to Nordenskiöld together with a letter dated January 23rd 1834. It has already been mentioned that these fragments resemble chrysoberyl in hardness and crystal form. The translation from French reads: "*The emerald mine has not provided any new material except the 2 small crystal fragments that I am sending to you, I would like to know your opinion about this mineral, which according to its hardness and the crystallisation has some resemblance with chrysoberyl.*"

Subsequently, in a letter dated May 24th 1834 (**Fig. 3.11**), five additional samples of alexandrite were sent to Nordenskiöld. The translation from French reads: "*I have the honour in sending you a mineral that I just received from Siberia, it was found in the Ural emerald mine. The two numbered samples are part of my private*

Fig. 3.10 Portrait of Count Lev Alekseevich Perovskii (1792–1856). Circa 1833 to 1834 Perovskii was the first to submit various alexandrite crystals from the emerald deposits in the Urals to the Russian Imperial Mineralogical Society for identification. In January and April 1834 he also sent alexandrite samples to Nordenskiöld in Helsinki for identification and further study. At the time of the alexandrite discovery Perovskii was Vice-President of the Appanage Department of the Russian Tsar, which, together with the Imperial Cabinet, received all emeralds that were mined from the Tokovaya area. Drawing by Franz Krüger, lithograph by Jentzen and published in the collection of Russian lithographies by Morosov (1913); Staatsbibliothek zu Berlin, Preußischer Kulturbesitz.

collection; as for the two others, they are for your collection; with the exception of the first two samples, these are the best specimens sent to me; besides I am also sending a small piece for analysis. After completion of your analyses, I would be grateful if you could send me the first two samples, with your opinion on this mineral; its uncommon tabular crystallisation, which consists in 3 prisms that cut each other crosswise by the middle; its hardness close to that of sapphire; its property to appear dark green in daylight and red when observed under candlelight, make me think that this is a new mineral. Moreover, we can

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[20] Eichwald (1870); Golynskaya and Svirina (1997).
[21] Personal communication from I. Fors (2009).

3.11 A letter from Count Perovskii to Nils von Nordenskiöld, dated May 24th 1834, that accompanied five alexandrite crystals for examination. Letter source: The Nordenskiöld family archive of the National Library of Finland, University of Helsinki, Finland.

observe its red colour even in daylight, but it is not as intense as under candlelight and is seen only in certain parts of the stone while the rest keeps its green colour."

Most interestingly, the letter contained a description of what is now referred to as the cyclic twins (trillings) of alexandrite, the colour change between daylight and incandescent light and the strong pleochroism of the samples.

The four drafts of letters from Nordenskiöld to Perovskii deal with information on economic minerals, such as the quality and cost of marble and barite, the shipping costs of ore from Finland to Russia (two drafts from the late 1830s) and research information about lapis lazuli from Baikal (two drafts from the early 1850s).

The draft of a letter from Nordenskiöld to Brewster is dated December 12th 1834 and accompanies the submission of one alexandrite crystal named cymophane, that was the English synonym for chrysoberyl at that time. Nordenskiöld was primarily interested in the unusual colour change of the material.

The drafts of letters from Nordenskiöld to his teacher Professor Berzelius (**Fig. 3.12**) in Stockholm, who became a close friend in the 1830s, cover the large field of mineral analyses. In one letter, dated February 1833, the discovery, properties and analysis of phenakite are described. In a draft written in October 1834, the properties of a new gemstone are described and its colour change between daylight and incandescent light is mentioned and admired. Because of these properties, the colour-change cymophane is designated as a mineral with the most striking and unusual properties that Nordenskiöld had ever seen. In a draft dated February 1837, Nordenskiöld again mentions Siberian minerals including colour-change cymophane.

The correspondence between Nordenskiöld and Berzelius was edited by Söderbaum[22] and covered 148 documents written between October 1817 and September 1847. The Library of the Stockholm Academy of Sciences possesses the originals of the letters from Nordenskiöld and copies of the letters from Berzelius, that were

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[22] Söderbaum (1927).

Fig. 3.12 Portrait of Jöns Jacob Berzelius (1779–1848). Berzelius was Professor of Chemistry in Stockholm and founder of modern chemical element analyses. In the 1820s, Nordenskiöld spent two lengthy periods of study and research in Berzelius' laboratory in Stockholm. From this time until Berzelius' death, a continuous correspondence is available, firstly between a professor and his former student and later between close friends. In the 1830s, Nordenskiöld discussed analytical problems with the new colour-change chrysoberyl variety with Berzelius and also sent him several samples for analysis and study. Painting by P.H. van den Heuvell, circa 1836, lithograph by F. J. Backer.

prepared at the end of the 19th century by A. E. Nordenskiöld. The first series of letters, until 1833, are respectful letters between a professor and his former student, but later reflect a correspondence between close friends: "My brother …". From the contents of these letters it is evident that the sequence is incomplete and that there were more written than are available. Some of the letters from Nordenskiöld that were edited by Söderbaum are identical to the drafts preserved in the Nordenskiöld family archive in Helsinki.

Letters Nos. 64 (February 1833), 65 (April 1833) and 68 (July 1833) describe the examination and naming of the new mineral species phenakite, the first samples of which had been received in the fall of 1832 from Perovskii. Several letters (Nos. 71, 74, 76) discuss the ongoing research on a possible new mineral that Nordenskiöld wanted to name in honour of Perovskii.

In letter No. 72 (August 24th 1834) Nordenskiöld describes his research on a mineral that did not prove to be a new species but a new variety of chrysoberyl. He writes (translated from Swedish): "*Peroffsky sent to me two or three months ago for investigation a rock specimen from the (emerald mines) of the Urals. Although the mineral is not a new species as Peroffsky believed, it is, however, very remarkable. It is chrysoberyl but occurs as large distinct crystals, partly as simple crystals, partly as trillings about 1 to 2 inches in diameter and they are already in that point of view uncommon but the remarkable thing is that they are in daylight grass-green resembling emerald in colour and are weakly transparent; in candlelight their transparency is clearly higher and the colour is like that of pyrope or staurolite from St. Gotthard, one cannot see any trace of green colour. As far as I know, there is no mineral with such a distinct phenomenon described above; there is no way to measure it. Peroffsky sent me also his specimens for investigation; the crystals were exceptionally beautiful in appearance, with some formerly unknown faces, which I have drawn. I keep some not so good specimens. Best of them I'll send to you or Kongl. Vetenskapsakademi[23] together with some other little things.*"

Several specimens of Siberian chrysoberyl were sent by Nordenskiöld to Berzelius between 1834 and 1837 (letters Nos. 73, 75, 82), and Berzelius carried out analyses of the material (letter No.107 by Berzelius, January 1840). As far as can be ascertained from this partly incomplete sequence of letters, their main interest was the evaluation of the cause of the colour change. Vanadium was discussed as a possible colour-causing trace element (letter No. 108 by Nordenskiöld, January 1840), and, finally Berzelius was able to prove the presence of vanadium from his analysis (letter No. 117, June 1841).

In summary, all available documents do confirm some of the details published later, especially those under the given name alexandrite in the 25th year anniversary volume of the Russian Imperial Mineralogical Society. Perovskii initially had two groups of alexandrite available, the first comprising small fragments of crystals, two of which he sent to Nordenskiöld in January 1834. The second group consisted of larger and better formed crystals (trillings) that he submitted to Nordenskiöld together with a letter dated May 1834. Nordenskiöld described colour-change cymophane in letters to Berzelius dated August and October 1834. He also sent one of the crystals to

[23] Royal Academy of Sciences.

Brewster in December 1834; this resulted in the first publication by Brewster in February 1835, shortly after having received this sample.

In the complete correspondence between Nordenskiöld and Berzelius written between 1837 and 1841, both use the names cymophane and chrysoberyl to describe what was later renamed alexandrite. Neither the documents found in the Nordenskiöld family archive in Helsinki nor any of the letters in the correspondence between Nordenskiöld and Berzelius edited by Söderbaum, use the name alexandrite.

According to published documents and unpublished letters from the Nordenskiöld family archive, it is evident that Nordenskiöld did not acquire any alexandrites in the Urals himself and only decided to examine some samples called emeralds when he realised that the material was chrysoberyl. Neither of these stories that are currently found on many internet websites is correct.

3.3   Emeralds and alexandrites from the Leuchtenberg, Koksharov and Kochubei collections

In the first volume of his "Materialien zur Mineralogie Russlands", Koksharov[24] only briefly mentions two extraordinary samples of Russian emerald from the Cabinet of the Emperor. This may indicate that, at that particular time, these samples were not available for scientific research. He cited the description of alexandrite by von Pott in the chapter about chrysoberyl and alexandrite in the fourth volume of his "Materialien zur Mineralogie Russlands".[25] However the chapters about alexandrite and emerald in the 1842 anniversary volume of the Russian Imperial Mineralogical Society are rarely cited by 20th century Russian authors. This indicates that this extremely rare book was not easily available in Russia.

3.3.1 Emeralds and alexandrites from the Leuchtenberg collection

The Leuchtenberg collection, part of the Mineralogische Staatssammlung (Bavarian State Collection for Mineralogy) housed in Munich, contains some "old" alexandrites. These, according to the history of the collection, provide some understanding into samples that were definitely found and preserved before 1850. The history of the collection also provides insight into the relationships between Maximilian, Duke of Leuchtenberg, and Tsar Alexander II and the Russian Imperial family. In this collection one of the two extraordinary emerald specimens from the Cabinet of the Emperor mentioned by von Pott is preserved.

Eugène de Beauharnais was the stepson of Napoléon Bonaparte, Emperor of France. In 1806 he married Princess Augusta Amalia of Bavaria, the daughter of the first Bavarian King Maximilian I. After the fall of Napoléon in 1814, the family moved to Munich. In 1817, his royal father-in-law made him Duke of Leuchtenberg and gave him the administration of the Principality of Eichstätt. In 1824 he died in Munich. There is little information about Eugène's mineral collection but it was enlarged by his son Auguste, the 2nd Duke of Leuchtenberg, who died childless in 1835.[26] He was succeeded by his younger brother, Maximilian de Beauharnais, who became the 3rd Duke of Leuchtenberg. Maximilian (**Fig. 3.13 a**), born in 1817, married Grand Duchess Maria Nikolayevna of Russia (**Fig. 3.13 b**), daughter of Tsar Nicolas I and sister of Tsarevich Alexander Nikolaevich in 1839. It has been mentioned that the Mariinsky Mine (now Malysheva Mine) was named in honour of Maria Nikolayevna.[27]

Tsar Nicolas I granted Maximilian the title of Imperial Highness, Prince Romanovskii (**Fig. 3.14**) and the couple remained in Russia.[28] In 1844, Maximilian became First Director of what is now the Saint Petersburg State Mining Institute and Technical University,[29] at that time the only technical university in Russia, a position he retained until his early death in 1852 (**Fig. 3.15**). Today, his picture can still be seen on one of the tables in the entrance hall of the Mining Institute in Saint Petersburg which describes its history. To honour his contribution to the

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[24]   "Materialien zur Mineralogie Russlands" (Materials of Russian Mineralogy) by Koksharov (1853b).
[25]   Published in 1862.
[26]   Pfaffl (1978).
[27]   Competent person's report on the Malyshev emerald mine, Sverdlovsk oblast, Russian Federation (2007).
[28]   Nicolas, July 2nd (1839); Grimm (1866); Diener (2008).
[29]   In the same time P. Schröder and S. Volkov are named as Second Directors, Amburger (1966).

Fig. 3.13 a Portrait of Maximilian Eugène Josephe Napoléon de Beauharnais, 3rd Duke of Leuchtenberg (1817–1852). In 1839 Maximilian married Maria Nikolayevna, daughter of Tsar Nicolas I and sister to Tsarevitch Alexander Nikolaevich, who became Tsar Alexander II in 1855. In 1844, Maximilian, now a Russian citizen and titled Prince Romanovskii, became Director of the Saint Petersburg Mining Institute. In this capacity he travelled to the Urals to inspect the mines, conduct geological studies and complete his mineral collection. The collection was moved to his own independent principality, Eichstätt that was located in the northern part of Bavaria, at that time. Painting by E. de Ron, circa 1840. By courtesy of R. Diener and reproduced with permission.

Fig. 3.13 b Portrait of Grand Duchess Maria Nikolayevna of Russia (1819–1876), daughter of Tsar Nicolas I and sister to Tsarevich Alexander Nikolaevich, later Tsar Alexander II. In 1839 Maria married Maximilian, Duke of Leuchtenberg, and became Duchess of Leuchtenberg. Lithograph by J. Velten, Saint Petersburg, circa 1840. By courtesy of R. Diener and reproduced with permission.

In 1855 the formal independence of the Principality of Eichstätt was annulled and the collection transported to Munich in the Bavarian State where it was merged with a collection of Russian minerals. On the initiative of Maximilian von Leuchtenberg, the latter collection had

Fig. 3.14 Coat-of-arms of Maximilian, Duke of Leuchtenberg, printed in his personal copy of Volume I of the "Schriften der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie" (1842). Photograph by K. Schmetzer.

mineralogy of Russia, Komonen named a member of the chlorite group "leuchtenbergite" in 1842.

Although Maximilian and Maria lived in the comfortable Mariinsky Palace in the centre of Saint Petersburg it was decided to relocate part of his famous mineral collection to Eichstätt in the second part of the 1840s. There, the collection was kept in the former summer residence of the Bishop of Eichstätt. These samples were combined with the existing collections of his father Eugène and his older brother Auguste that had been on public display since 1831.[30]

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[30]   Pfaffl (1978).

Fig. 3.15 Portrait of Maximilian, Duke of Leuchtenberg, Prince Romanovskii, pictured in one of the plates on display in the entrance hall of the Mining Institute in Saint Petersburg that describes the history of the school and mineralogical museum. Photograph by K. Schmetzer.

Fig. 3.16 a and b Cyclic twins (trillings) of alexandrite from the Tokovaya area, Urals, Russia. Mineralogische Staatssammlung Munich, (a) size 4 x 4 cm, (b) size 2 x 2 cm. Photographs by K. Schmetzer.

Fig. 3.17 Crystal group of cyclic twins (trillings) of alexandrite from the Tokovaya area, Urals, Russia. Mineralogische Staatssammlung Munich, size 5 x 9 cm. Photograph by K. Schmetzer.

Fig. 3.18 Faceted alexandrite from the Tokovaya area, Urals, Russia. Mineralogische Staatssammlung Munich, weight 1.33 ct. Photograph by K. Schmetzer.

been donated by himself in the second half of the 1840s [31] and by the Russian Academy of Science to the Bavarian Academy of Science.[32] From the old inventories, it is possible to identify those alexandrites in the Munich collection that can be dated back to the late 1840s or 1850s. The collection[33] contains some alexandrite trillings (**Fig. 3.16**) and a larger crystal group (**Fig. 3.17**). A faceted gemstone of 1.33 ct (**Fig. 3.18**) is the oldest historical piece that was microscopically studied during this research project.

In addition to these alexandrites, the famous ***Leuchtenberg emerald druse*** with phlogopite matrix (**Fig. 3.19**) forms part of the collection. The emerald sample, found in 1831, was examined at the Mining Institute in Saint Petersburg before Tsar Nicolas I gave it to his son-in-law Maximilian, Duke of Leuchtenberg as a birthday present. A detailed drawing of the sample,

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[31] Königliche bayerische Akademie der Wissenschaften (1847).
[32] Personal communication from R. Hochleitner (2009).
[33] See also Groth (1891).

Fig. 3.19 Emerald crystals-in-matrix from the Tokovaya area, Urals, Russia. Mineralogische Staatssammlung Munich, size 31 x 32 cm, weight 6 265 g. Known as the **Leuchtenberg emerald druse**, it was found in 1831 and came into the Cabinet of Tsar Nicolas I. It was presented to his son-in-law, Maximilian von Leuchtenberg, on his birthday and came into his mineral collection at Eichstätt in the late 1840s. Photograph by courtesy of the Mineralogische Staatssammlung Munich.

prepared in the 1840s, is still kept at the Mining Institute and was recently published.[34] Comparing this drawing with a photograph of the sample (**Fig. 3.19**), it can be seen that one emerald crystal and some matrix material has since broken away (see arrow in Fig. 3.19).

A first short description of an emerald crystal group of that size dates back to January 1832.[35] It is obvious that this sample, consisting of more than 20 emerald crystals in matrix, as described by von Pott may be the **Leuchtenberg emerald druse**. The dimensions given roughly fit with the sample kept in the Munich collection, but, for an irregularly shaped piece, these would be largely dependent on the measurement direction selected. The weight given in 1842 recalculated to 6270 grams is close to the actual weight of 6265 grams.[36] The difference can be explained by taking into consideration the crystal lost at the edge of the sample. Thus, the first sample from the Cabinet of the Emperor described in the 1842 anniversary volume can now be identified as the **Leuchtenberg emerald druse**.

The oldest son of Maximilian, Duke of Leuchtenberg, also played an important role in Russian mineralogy in the 19th century. Nicolas, Duke of Leuchtenberg (1843-1891) was a passionate mineral collector and friend of Nicolai von Koksharov and Prince Petr Kochubei.[37] Some extraordinary samples in his collection are described in the various volumes of Koksharov's Russian Mineralogy. Koksharov also mentioned a journey he made to the Urals together with Nicolas von Leuchtenberg, who was President of the Russian Mineralogical Society from 1865 to 1890. Following his death, Nicholas' mineral collection was given by his widow to the Mining Institute in Saint Petersburg, and was one of their most valuable acquisitions at the end of the 19th century.[38]

3.3.2 The largest alexandrites – samples and brief history of the Kochubei and Koksharov collections

The most famous alexandrite crystal group originating from the Krasnobolotsky Mine was found in 1839 or

[34] Zhernakov (2009).
[35] Struve (1832); see section 3.3.3.
[36] Personal communication from R. Hochleitner (2008).
[37] For the complete family history see Sakharov (1998), Diener (2009); see also section 3.3.2.
[38] Devnina et al. (1994).
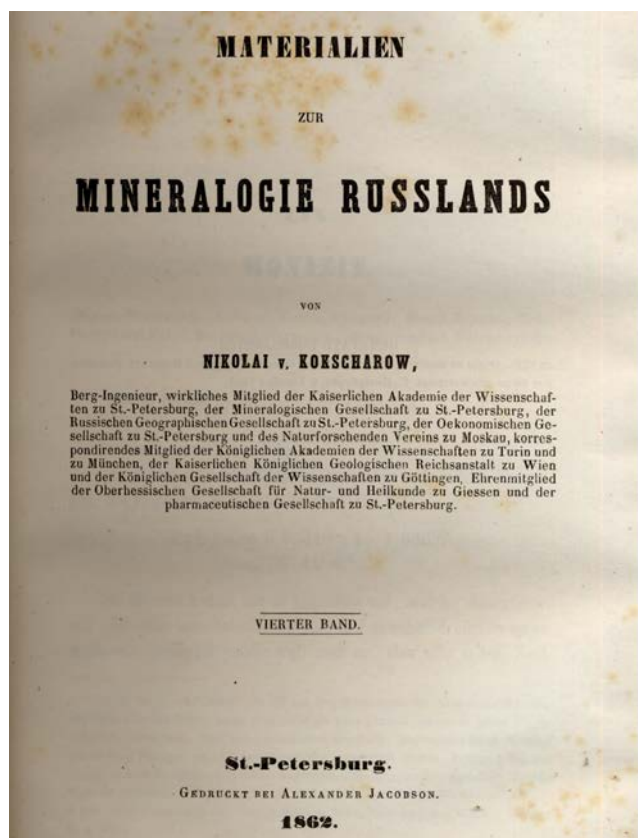
Fig. 3.20 Volume 4 of Koksharov's "Materialien zur Mineralogie Russlands" (1862a) contains a detailed morphological study of single alexandrite crystals and trillings from the emerald fields in the Urals. This book also contains a drawing of the largest crystal group of alexandrites that was ever found in Russia, known now as **Kochubei's druse** (refer to title figure of chapter 6); the same drawing was also published in a separate monograph on alexandrite by Koksharov (1862b). Photograph by P. Reith.

Fig. 3.21 Portrait of Petr Arkadevich Kochubei (1825–1892). Prince Kochubei was a passionate mineral collector and close friend of von Koksharov. He bought the Perovskii collection in 1856; this most probably contained the largest alexandrite crystal group ever found in Russia which became **Kochubei's druse**. Kochubei's collection also contained the largest emerald crystal that was mined in the Urals in the 19th century and known as the **Kochubei emerald** (see Figure 3.25). Photograph from the collection of the Library of the Moscow Society of Naturalists by courtesy of E. Minina.

1840.[39] It is known in the literature as **Kochubei's druse**[40] and was pictured and described by Koksharov in his 1862 book "Materialien zur Mineralogie Russlands, Vierter Band" (**Fig. 3.20**) and in his 1862 monograph about alexandrite.

Prince Petr Arkadevich Kochubei (1825–1892, **Fig. 3.21**)[41], who started his mineral collection in the 1840s, was later a member of a mineralogical circle in Saint Petersburg and a friend of Nicolas, Duke of Leuchtenberg. Kochubei shared his mineralogical interests with many scientists such as A.V. Gadolin and N.I.

Koksharov. He purchased Perovskii's private collection after his death in 1856. Up to now, no catalogue or other list of samples transferred from the Perovskii collection to Kochubei is mentioned in Russian literature. We can only speculate which samples originated from Perovskii and which samples were added to Kochubei's collection before or after 1856.

After Kochubei's death in 1892, his mineral collection was kept in his private country estate, and part of it was lost when the house burnt down in 1905. Later, Kochubei's son moved the collection to Kiev in the Ukraine and thence to Vienna in Austria. In 1908, the collection was catalogued and negotiations with museums began for its sale. In 1910, the collection was offered to the Russian Academy of Sciences and evaluated by V.I. Vernadsky and A.E. Fersman during 1911. After lengthy negotiations the collection was purchased in 1913 for

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[39] Refer to title figure of chapter 6.
[40] Fersman (1929); Lyckberg (1993); Kozlov (2005); Bukanov (2006).
[41] A detailed description of the life of Prince Kochubei was published by Sreznevskii (1893) and the history of his collection was compiled by Moisseeva (2003).

Fig. 3.22 An alexandrite trilling from the Koksharov collection, housed at the Natural History Museum, London since 1865 is the largest Russian alexandrite crystal examined in this study. The original label is written in German, most probably by Koksharov himself. The diameter of the crystal is 7.5 cm. Photograph by K. Schmetzer.

165 000 roubles (prices between 100 000 and 300 000 had been discussed) and was moved to Saint Petersburg. In 1934 the collection was moved to Moscow with the museum.

The largest alexandrite crystal group ever found in Russia is one of the most valuable specimens of the Kochubei collection. It is now housed in the Fersman Museum in Moscow[42] and consists of a 5.38 kg[43] aggregate of 22 crystals, the largest with a diameter slightly over 7 cm. This sample had previously been described by Koksharov in 1862 and published as a lithograph. Using Koksharov's data the sample weight was recalculated as 5379 grams. He also mentioned that the druse was unearthed in 1840 and most probably originated from the Perovskii collection. This crystal group known as ***Kochubei's druse*** was used as the symbol of Fersman Museum that houses the oldest mineral collection in Russia. In commemoration of the date celebrating the 250th anniversary of the museum (1716 to 1966) a special medal that used the druse as its emblem was struck.

The largest Russian alexandrite trilling seen by the author (**Fig. 3.22**) is preserved in the Natural History Museum in London and originates from the Koksharov collection.

Nicolai Ivanovich von Koksharov (1818–1892; **Fig. 3.23**) is the most famous Russian mineralogist and crystallographer of the 19th century. He was educated at the Mining Institute in Saint Petersburg in the 1830s and devoted his scientific career to the study of crystal morphology and the teaching of mineralogy and crystallography. In 11 volumes of his "Materialien zur Mineralogie Russlands" published between1853 to 1891,[44] Koksharov detailed mineralogical and crystallographic descriptions of numerous mineral species. He was elected Director of the Russian Imperial Mineralogical Society from 1865 to 1891 and Director of the Saint Petersburg Mining Institute from 1872 to 1881, losing this position after one of his students was involved in the assassination of Tsar Alexander II in 1881.[45]

Koksharov's collection was described as containing samples comparable to, or even better than, those housed in the Saint Petersburg Mining Museum.[46] This collection included numerous samples of tourmaline, topaz, beryl and alexandrite (**Fig. 3.24**) and was sold in

[42] Refer to title figure of chapter 6.
[43] Fersman (1961).
[44] In German, the first volumes also published in Russian.
[45] Kulibin (1892); Bessudnova (2006).
[46] Roemer (1862).

Fig. 3.23 Portrait of Nicolai Ivanovich von Koksharov (1818–1892), one of the most famous Russian minera-logists and crystallographers of the 19th century. Koksharov was Director of the Russian Imperial Minera-logical Society (1865–1891) and Director of the Saint Petersburg Mining Institute (1872–1881). His main work was published as "Materialien zur Mineralogie Russlands" in 11 volumes (1853–1891/1892) together with an "Atlas" (1853). In Volume 4 (1862a) he published a de-tailed mineralogical description of alexandrite; the "Atlas" contains the first detailed crystal drawings of alexandrite trillings showing different habits. Photo-graph circa 1865, on display at the Mineralogical Mu-seum of Saint Petersburg State University, Saint Peters-burg. Photograph by K. Schmetzer.

Fig. 3.24 Tabular alexandrite cry-stals-in-matrix, Koksharov collec-tion. From the Museum of Natural History, London, Size 1.5 x 2.5 cm. Photograph by K. Schmetzer.

1865 to the British Museum, and later transferred with other geological samples to the collection at the Natural History Museum.[47] The largest alexandrite trilling in London, originating from the Koksharov collection (**Fig. 3.22**), measures approximately 7.5 cm diagonally through the middle of the edges of the hexagon and approximately 8 cm diagonally through the tips of the hexagon (viewed parallel to the a-axis). Samples with a diameter of up to 9 cm, occasionally mentioned in the literature, have never been seen in any of the museums visited by the author.

Other large alexandrite crystal groups from the 19th century have not been documented, although some out-standing samples, often dated from the 1840s, are housed in various museums such as in Vienna, London and Munich.[48] Since 1980, four outstanding alexandrite crystals or crystal groups have been found in the Maly-sheva Mine. These unique samples weigh 446, 207, 161 and 66 grams, respectively.[49]

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[47] British Museum (1904).
[48] Refer to title figure of chapter 3, 6 and 9 and figure 3.17.
[49] Competent person's report on the Malyshev emerald mine, Sverdlovsk oblast, Russian Federation (2007); these four alexandrite samples are pictured by Zhernakov (2009).

Fig. 3.25 a The emerald crystal shown here was found at the Sretensky Mine in 1831and is now housed in the Fersman Mineralogical Museum, Moscow. The crystal, **Kochubei's emerald**, measures 10 x 18 cm and weighs 2226 g. The length was measured from the top right to the base. The sample originated from Prince Kochubei's collection and came into the Fersman Museum in 1913 from Vienna (see section 3.3.2). Photograph by E. Sokolova.

Fig. 3.25 b The 1842 Volume of the Russian Imperial Mineralogical Society contains several drawings of emerald crystals mined from the Tokovaya gemstone belt. The sample pictured is described as belonging to the Cabinet of the Emperor, size 10 x 18 cm, weight 2226 g; the natural appearance of the sample is achieved by minute mica flakes glued on to the hand coloured plate. Photograph by P. Reith.

Fig. 3.25 c Photograph of the **Kochubei emerald**, published in 1961 in a book under the name of A. Ye. Fersman. In a chapter devoted to the history of this emerald it is erroneously assumed to be the **"Kokovin emerald"**, which was lost in 1835.

3.3.3 Kokovin's or Kochubei's emerald?

The Fersman Museum also contains a 2226 gram emerald crystal with micaceous matrix that originates from the Kochubei collection (**Fig. 3.25a**). This sample referred to as "***Kokovin's emerald***" but recent research indicates there are some errors and misunderstandings in the literature. The ownership of this sample can only be reliably traced to Kochubei and not to Kokovin as the so-called "***Kokovin's emerald***" weighed approximately 400 grams.[50]

There are two topics to discuss; the fate of Kokovin and the identity of the stolen or lost emerald. There are different versions quoted for both historical events.[51] In 1923, Fersman mentions three primary sources of relevant documents; the archives of the Imperial Cabinet, the Appanage Department and the stone cutting factory in Ekaterinburg. Both the Imperial Cabinet and the Appanage Department shared the cost for emerald

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[50]   Moisseeva (2003); see also Zhernakov (2009).
[51]   One by Fersman (1923, 1947, 1961) and the other by Semyonov and Shakino (1982).

Fig. 3.26 Portrait of Count Lev Alekseevich Perovskii (1792–1856). At the time when the first alexandrites were discovered, Perovskii was Vice-President of the Appanage Department, he became Minister of the Interior in 1841 and in 1852 Minister of the Appanages and President of the Imperial Cabinet. In 1847 Perovskii sold numerous samples from his mineral collection to the Museum of the Mining Institute in Saint Petersburg, including several emerald and alexandrite crystals. Portrait by E.I. Botman, 1875 is a copy of an older portrait. State Memorial Museum of A.V. Suvorov, Saint Petersburg by courtesy of E. Minina.

In both versions, Count Lev Alekseevich Perovskii plays an important role in Kokovin's downfall. In 1831, Perovskii (1792–1856, **Fig. 3.26**) was Vice-President of the Appanage Department; he became Minister of the Interior in 1841 and Minister of Appanages and President (Dirigent) of the Imperial Cabinet in 1852.[55] He is also mentioned in the list of honorary members of the "Russisch-Kaiserlichen Gesellschaft für die Gesammte Mineralogie", published in 1842. Perovskii was a passionate mineral collector and it is commented … "He used to take advantage of his rank to fill his collection" and "All the best stones that went to the Appanage Department settled down in the Vice-President's Cabinet".[56] In spite of this Golowin,[57] in his highly critical book, ajudges Perovskii's administration and work as Minister of the Interior positively, in contrast to most of the other

Fig. 3.27 Portrait of Tsar Nicolas I (1796–1855) Emperor from 1825. By an unknown artist, circa 1845; Berlin-Lichterfelde, Johanniterorden, Collection Werner. Copyright bpk Bildagentur für Kunst, Kultur und Geschichte, Berlin. Photograph by Jürgen Liepe, reproduced with permission.

exploration and mining.[52] Reports by Kokovin and his successor Veits, Directors of the Ekaterinburg stone cutting factory in the 1830s, were addressed to one or other of these government institutions. However, the only factual, referenced document was published by Fersman in 1923;[53] other papers that have been written are without factual proof from the primary documents with no mention of such documents in reference lists. Different Russian authors in general followed one or the other of these two versions.[54]

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[52] von Pott (1842b); Svirina (1994); Semyonov and Timofeev (2005).
[53] The report of Khroshevitskii dated 1835, an examiner of the Appanage Department who was sent out to Ekaterinburg.
[54] See e.g. Emlin (1996); Burlakov et al. (1997); Avdonin and Polenov (2002); Moisseeva (2003); Kozlov (2005); Semyonov and Timofeev (2005).
[55] Pierer's Universal-Lexikon (1861); Amburger (1966); for details about Appanage Department, Ministry of Appanages, Department Udelov see Amburger (1966) and Blum (1971).
[56] Semyonov and Shakino (1982); Moisseeva (2003).
[57] Golowin (1845).

ministers of the Imperial Cabinet who are considered a group of incapable persons. Additionally, it is also mentioned that Perovskii tried to improve the economic well-being of the Appanage peasants.[58] It has already been mentioned that after his death Perovskii's collection was bought by Prince Kochubei.

Yakov Vasilevich Kokovin was head of the Ekaterinburg stone cutting factory and, after 1831 was in charge of emerald prospecting and the mining of deposits in the Tokovaya area, especially from the Sretensky Mine. There is no question that prior to 1835, the relationship between Kokovin and Perovskii was full of tension. In 1835, Kokovin was accused of misusing his position and stealing some of the best emerald crystals as well as other items. Although there are different versions of this tragedy, it is certain that Perovskii initiated an investigation of Kokovin's work in June 1835. Further developments even personally involved Tsar Nicolas (**Fig. 3.27**) and Kokovin was imprisoned in December 1835. In Ferman's version (**Fig. 3.28**) Kokovin committed suicide after some years. Other more recent versions[59] contend that he was released from prison in 1839. His health was poor as a consequence of losing his position and all the honours bestowed on him for his work as a lapidary artist and stone cutter (in the 1820s) and for the discovery and exploitation of the emerald deposits (in the 1830s). He attempted to re-open his case but died in 1840.

Directly connected to Kokovin's tragedy is the mystery concerning the missing emerald of extraordinary quality. An inspector,[60] sent by the Appanage Department in 1835 examined Kokovin's house collecting and listing all samples he found in his private apartment and offices. Among these numerous specimens of emerald, amethyst, aquamarine and others was an emerald crystal of extraordinary quality that warranted special mention in the report. No dimensions were recorded but the weight was stated to be about one Russian pound, which is about 400 grams. All the samples were packed in boxes and sent to the Appanage Department in Saint Petersburg. Following a reinspection of these boxes it was established that this emerald crystal had disappeared. All Russian authors agree that a member of high rank within the Appanage Department, probably Perovskii, had taken the emerald.

Fig. 3.28 Portrait of Alexander Yevgenyevich Fersman (1883–1945), one of the most famous Russian mineralogists and geologists of the 20th century (see Kamenev, 1995; Novgorodova and Leybov, 2008). Professor Fersman devoted some of his studies to geochemical problems, particularly to the migration of elements during geological and geochemical processes. A summary of his work on the formation of emeralds in the Tokovaya gemstone belt was published in 1929. In connection with alexandrite and emerald, he was one of the official Russian evaluators of the Kochubei collection in Vienna (1911) and editor of the catalogue "Russia's treasure of diamonds and precious stones" (1925, 1926). Picture on display at the Vernadsky State Geological Museum, Moscow. Photograph by K. Schmetzer.

There are two different explanations describing the later history of this specimen. A book about the history of gem materials, edited under the name of Fersman in 1961, describing semitransparent or opaque materials used for decorative objects such as vases, includes a chapter describing Kokovin's tragedy. It is concluded that the 2226 gram emerald, part of the Kochubei collection that returned to Russia from Vienna in the early 20th century and now preserved in the Fersman Museum in Moscow, is identical to the emerald previously recorded from Kokovin's house. More recent papers[61] conclude that the original emerald found in Kokovin's house by in-

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58 Blum (1971).
59 Semyonov and Shakino (1982); Semyonov (2003).
60 Named Khroshevitskii by Fersman (1923) and Yaroshevitskii in more recent Russian texts.
61 See e.g. Semyonov and Shakino (1982); Moisseeva (2003); Semyonov and Timofeev (2005); Zhernakov (2009).

spector Yaroshevitskii is lost. The main argument supporting this conclusion is the discrepancy in the weight of the emerald; approximately 400 grams versus 2226 grams.

It is stated that the possible error in Fersman's 1961 book was a mistake by the editor, who prepared Fersman's texts more than one decade after his death in 1945. However, there is an identical version directly related to Fersman that correlates the 2226 gram specimen with the lost **Kokovin emerald**. This was published in English[62] as part of a series on "Jewels in the Russian diamond fund". Part one mentions that this is a direct translation of an article that appeared in the Russian magazine "Novyi mir" in 1946. It is probable that this article was directly related to Fersman and no major changes were made by the editorial staff in 1946.

If Fersman's version is incorrect the question of the origin of the 2226 gram emerald in the Kochubei collection remains. There are only a limited number of samples of comparable size that were found in the Russian emerald mines in the 19th century. As already stated[63] only two extraordinary samples are mentioned by von Pott, one of which is now identified as the **Leuchtenberg emerald druse**. The second extraordinary sample was pictured in the 1842 book (**Fig. 3.25 b**) with the colour drawings of an alexandrite crystal group in daylight and incandescent light. It was mentioned that this emerald crystal belonged to the Cabinet of the Emperor (p. 56). The photograph published in Fersman's 1961 book (**Fig. 3.25 c**) is not helpful because the sample pictured in the 1842 book is in another orientation. However, a more recent photograph taken by Elena Sokolova in the Fersman Museum during 2009 (**Fig. 3.25 a**) definitely proves that both samples are the same.

In the literature there is some debate about the year that the **Kochubei emerald** was excavated but there are no direct references. A recently discovered document may clarify this point. In a short note dated January 17th 1832, von Struve mentions two extraordinary emerald samples from the Cabinet of the Emperor. According to the sizes and descriptions given these could be the **Kochubei emerald** and the **Leuchtenberg druse**, proving that 1831 was the most probable year of excavation of both samples. H.C.G. von Struve (1772–1851; **Fig. 3.29**), a passionate mineral collector, was a Russian diplomat

Fig. 3.29 Portrait of Heinrich Christopher Gottfried von Struve (1772–1851), a Russian diplomat who resided in Hamburg, Germany. Von Struve was a passionate mineral collector, and sent a letter dated January 17th 1832 to the editor of the "Jahrbuch für Mineralogie, Geognosie, Geologie und Petrefaktenkunde" in which he reported new finds of emeralds in Russia. Two notable samples mentioned are most likely the **Leuchtenberg emerald druse** and the **Kochubei emerald**. Lithograph by J. Velten, Carlsruhe. By courtesy of Fersman Museum, Moscow.

and Minister-Resident in Hamburg, Germany. A great part of his collection is preserved at the Fersman Mineralogical Museum, Moscow.[64]

However, there is an apparent gap in information between the mention in the 1842 book when the sample was housed in the Cabinet of the Emperor to that in the early 20th century when Kochubei's collection was purchased by the Russian government and moved from Vienna. In the first volume of Koksharov's books on Russian mineralogy, two extraordinary samples that approximate in size to the **Leuchtenberg druse** and the **Kochubei emerald** are only briefly mentioned and no

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[62] Fersman (Part IV, Gems and Gemology, 1947).
[63] See section 3.1.
[64] Novgorodova and Mokhova (2005).

further information on these two Uralian emeralds is given.[65]

Some recent publications make the assumption that the **Kochubei emerald** came into Kochubei's collection when he bought the complete Perovskii collection after his death in 1856. However, according to what is known by this author (KS), there are no documents available that unequivocally prove this assumption.

A recent description gives some insight into the magnificent Perovskii collection.[66]

In her paper E. Svirina mentions that, in 1847, the Mining Museum of the Mining Institute in Saint Petersburg purchased a suite of minerals, including Uralian emeralds, from Perovskii for 32 000 roubles. This purchase of about 2000 (!) samples from Perovskii's private collection was done by special order of Tsar Nicolas I.[67] When compared to the annual income of 400 roubles that Koksharov earned as a Captain in the Saint Petersburg Mining Corps in 1846,[68] we can imagine the enormity of this sum.

In her paper published in1994, Svirina includes Perovskii's bibliographic data and describes how he was able to acquire such an extraordinary collection of superb mineral specimens. She mentions his connections to Kokovin in Ekaterinburg and his position as Vice-President of the Appanage Department through which he … "was able to assemble his beautiful collection".

In summary the **Kochubei emerald** and the sample described and pictured in 1842 from the Cabinet of the Emperor can be proven to be one and the same. However, we can only trace the history of this emerald (**Fig. 3.25 a–c**) initially from its excavation in 1831 to the Cabinet of the Emperor in 1842 and later as part of the Kochubei collection which was sent from Vienna to Saint Petersburg in 1913. The specimen is now preserved in the Fersman Mineralogical Museum, Moscow. From the circumstances described, the missing link between the Cabinet of the Emperor and the Kochubei collection could have been the Perovskii collection, but it is not clear in what way and at what date this extraordinary emerald left the Cabinet of the Emperor.

3.4 The naming of alexandrite

As has already been mentioned in section 3.1, in 1833 four samples that had been discovered in the Uralian emerald mines were submitted for investigation by Count L. A. Perovskii to the Russian Imperial Mineralogical Society in Saint Petersburg. Franz von Wörth identified these crystals as chrysoberyl. Additional samples submitted to von Wörth in 1834 confirmed the first identification. According to a note by Brewster dated 1835, Nils von Nordenskiöld made the same observations on samples obtained from Perovskii in the spring of 1834. Nordenskiöld sent one of these crystals to Brewster for further testing. The identification of the first alexandrites as chrysoberyl was obviously not easy because of the quality of the first crystals and crystal fragments and the fact that only cyclic twins (trillings) and no single crystals were available.

According to the 25th anniversary volume of the Russian Imperial Mineralogical Society, it was Nordenskiöld who suggested that this colour-change gem variety of chrysoberyl should be named **ALEXANDRITE** in honour of the Tsarevich Alexander Nikolaevich (**Fig. 3.30**) who became Tsar Alexander II, reigning from 1855 to 1881. It was stated that he celebrated his coming of age on the day the mineral was discovered in the Urals. This volume was prepared in the spring of 1842 and passed by the censor on April 17th 1842. Obviously it was intended to be available in time for the silver wedding of Tsar Nicolas I,[69] a great event celebrated on the 1st July 1842.

Tsarevich Alexander Nikolaevich, the future Tsar Alexander II, was born in April 17th [Jul.]/29th [Greg.] 1818[70] and came of age on his 16th birthday, which was celebrated at the end of April 1834.[71] A public ceremony

65 Koksharov (1853b), referring to a short note in Gornyi Zhurnal, Vol. 1834, Part 3, p. 154.
66 Svirina (1994).
67 Personal communication from E. Svirina (2009).
68 Bessudnova (2006).
69 An event already mentioned in the introduction of this book.
70 See footnote 4.
71 Early May 1834 after the Gregorian calendar; Venturini (1836); Grimm (1866); Halvorsen and Molesworth (2007).

Fig. 3.30 Tsarevich Alexander Nikolaevich (1818–1881) on horseback. Emperor of Russia from 1855. Painting by Egor Botman after Franz Krüger, circa 1850. Picture on display in the Hermitage Museum, Saint Petersburg. Photograph by K. Schmetzer.

was performed in Saint Petersburg for this occasion. At that time it was a tradition in the Russian monarchy to celebrate the coming of age at 16 years. The discrepancy between this date (end of April/beginning of May 1834) and the discovery of the first alexandrites in 1833 was never a problem for Russian authors. The naming of the mineral and its discovery have always been linked with the coming of age of Alexander and used in subsequent descriptions about Russian alexandrite.

In his 1862 book Koksharov describes the discovery of chrysoberyl, closely following the details already published in the 1842 volume. On page 56, he comments that the first colour-change chrysoberyl (alexandrite) crystals were discovered in the Urals on the day when the Tsarevich came of age (this was April 1834). Furthermore,

he mentions on page 57, that the first alexandrite crystals were submitted to von Wörth for examination by Perovskii in 1833. This story is repeated by von Kobell in 1864 who mentions that the first crystals were discovered in the Urals in 1833. At the suggestion of Nordenskiöld this chrysoberyl variety was named **ALEXANDRITE** because it was discovered on the day that the Tsarevich celebrated his coming of age. He also mentions that Perovskii discovered the colour change effect.

Since their discovery in 1831 the Uralian emerald mines were controlled by both the Imperial Cabinet and the Ministry of Appanages (also Appanage Department, Department Udelov; **Fig. 3.31**) which was responsible for the private properties and income of the Imperial family.[72] In the summer 1853, Perovskii instructed Grewingk to examine the emerald mines and determine the cause of the continuing decrease in emerald production. According to his report that included the first geological map of the Uralian emerald belt, Grewingk found only one partly working mine with most trenches, holes and pits flooded. In later decades, the emerald mines were leased and subleased under various conditions to both Russian and foreign companies.[73]

In the 2005 English version of his book about alexandrite, Yu.S. Kozlov published a letter from Kokovin to Prince Gagarin, the Vice-President of the Imperial Cabinet. Gagarin (1784–1842) is also mentioned in the list of honorary members of the "Russisch-Kaiserlichen Gesellschaft für die Gesammte Mineralogie", holding this Cabinet position from 1833 to 1842. Kokovin's letter was also published in two Russian books.[74] Unfortunately, in all three books mentioned, the letter is neither dated nor is its detailed source given.

A search by Peter Lyckberg, at the request of the author, finally solved this problem. The letter is dated June 16th 1834 and is preserved as Kokovin's letter No. 421 in the Governmental Archives of Sverdlovskaya Oblast (Ekaterinburg Region).[75] The document was discovered by V.B. Semyonov around 1997 during his research on the history of the Tokovaya emerald deposits.[76]

Kokovin's letter to Gagarin reports the discovery of several crystals of what was probably a new mineral in a

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[72] Von Pott (1842b); Grewingk (1854); Svirina (1994); Semyonov and Timofeev (2005).
[73] See also chapter 2.
[74] Kozlov (2003), as well as Avdonin and Polenov (2002).
[75] Vainera Street 17, Ekaterinburg, 620014 Russia (http://www.midural.ru/gov/Docs/Ministr/arch/newpage4.htm). The exact location of the document is: Fond 36 (part of archive is number 36), description 1, document 660, pages 131-135 (personal communications from P. Lyckberg and V.B. Semyonov, 2009).
[76] See the detailed documentation about history of Uralian emeralds by Semyonov and Timofeev (2005).

Emperor Tsar Nicolas I

**Appanage Department
(Department Udelov)**
Minister of Appanages P.M. Volkonskii
Vice-President of Appanage Department
L.A. Perovskii

Imperial Cabinet
Dirigent of Imperial Cabinet
P.M. Volkonskii
Vice-President N.S. Gagarin

emeraldes and
alexandrites as
yield of mining
activities

instructions and finance
for emerald prospection
and mining

emeralds and
alexandrites as
yield of mining
activities

**Head of Ekaterinburg Lapidary Plant
Ya.V. Kokovin**

Fig. 3.31 Organisational chart showing the command structure for the mining of emeralds at around 1833 to1834 when the first alexandrites were discovered. Finance was given by both the Appanage Department and the Imperial Cabinet and the mine yield was shared between both Departments of the Imperial organisations. Artwork by K. Schmetzer.

vein that was worked during emerald mining. The letter describes some crystals and faceted stones of this unknown mineral that show a remarkable colour-change feature from dark green in daylight to crimson red in incandescent light. It also mentions that during faceting this new mineral was found to have a relatively high hardness comparable to that of sapphire. The first samples found in 1833 were handed to the Vice-President of the Department Udelov and a second parcel of samples was given to that same person in April 1834.

In all previous publications,[77] the text of Kokovin's letter mentions that the alexandrites were given to the Vice-President of the Department of Uyezds. In the Russian Empire, Department Uyezds is responsible for the administration of provinces, so this comment doesn't really make sense. Kokovin had to report directly to the Imperial Cabinet and/or to the Appanage Department (Department Udelov; **Fig. 3.31**). In the Russian original text of Kokovin's letter, submitted by V.B. Semyonov to the author, it states that the samples were submitted to the Vice-President of the Department Udelov, who is unequivocally identified at this time as Count L.A. Perovskii.

This letter provides the definitive announcement of the finding of the first crystals of the mineral that later became known as alexandrite. All the details fit the known

circumstances: the first alexandrite crystals were received by Perovskii in two lots in late 1833 and in the spring of 1834. The first few small crystals were submitted to von Wörth for examination and two fragments were also sent to Nordenskiöld in January 1834. Samples from the second lot, including the first complete trillings, were given to both von Wörth and Nordenskiöld in May 1834; the latter sent one of his crystals to Brewster in Scotland in December 1834. Based on the information in Kokovin's letter it is now understandable why the discoverer of the first samples of alexandrite was never mentioned. In 1837 the Tsarevich visited Ekaterinburg and the Urals and was told of Kokovin's tragedy. Alexander was informed that Kokovin was still in prison.[78] Furthermore, Tsar Nicolas' personal involvement in the case centred on the supposed lost Kokovin emerald was already mentioned in section 3.3.3.

Nordenskiöld (**Fig. 3.32**) remained in close contact and on good terms with Perovskii for more than 20 years from the early 1830s. The first letter from Perovskii found in the Nordenskiöld family archive, dates from November 1831 and deals with the submission of some of the first emeralds found in the Urals. The last letter dated November 1852 deals with a research project on lapis lazuli. The last draft of a letter from Nordenskiöld to Perovskii is in April 1853 and contains some results of the

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[77]   In the book by Avdonin and Polenov (2002) about Uralian minerals as well as in the Russian and English editions of Kozlov's alexandrite book (2003, 2005).
[78]   Kaluzhsky (2001).

Fig. 3.32 Nils Gustaf Nordenskiöld (1792–1866) on the left shown together with Alexander von Nordmann (1803–1866) in the centre and Karl Eduard von Eichwald (1795–1876) on the right. Nordenskiöld was involved in the examination of the first alexandrites in 1834 and, in 1842 he suggested naming the new colour-change variety of chrysoberyl as alexandrite in honour of the Tsarevich, who later became Tsar Alexander II. Photograph by C.A. Hårdh, 1864. National Board of Antiquities, Archives for Prints and Photographs, Helsinki, Finland.

lapis lazuli research project.[79] In 1833 Nordenskiöld was working on the description of a possible new mineral that he wanted to name in honour of Perovskii[80] and in a reply

dated January 23rd 1834, Perovskii writes that he is pleased about this idea. However, because of analytical problems, this research work was never finished.[81] The naming of a new mineral in honour of Perovskii, perovskite, was done some years later by Rose who also published the first mineralogical description of alexandrite.[82]

Between 1833 and 1834 Nordenskiöld was working on another new beryllium mineral named phenakite, he briefly mentions it in a paper published 1833 and described it in detail in 1834. The material was discovered in samples from the Urals and had been sent to him by Perovskii.[83] Between 1846 and 1847 Nordenskiöld described diphanite, another new mineral, also sent to him by Perovskii.[84] In 1857, as was already mentioned, Nordenskiöld published a description of lazurite from samples given to him by Perovskii in 1852. Thus Nordenskiöld described several new mineral species and varieties from the Urals in the 1830s and 1840s, although his first visit there was in 1849.[85]

Nordenskiöld always considered colour-change chrysoberyl or cymophane as a mineral with extraordinary properties,[86] although no publication by him on this variety has been found prior to the naming of alexandrite in 1842. Several reasons could explain this: possibly he concentrated on describing phenakite, a new mineral, in 1833 to 1834, or because the chrysoberyl variety, that later became alexandrite, was not a new mineral species and had already been identified by von Wörth in Saint Petersburg and confirmed by himself.

It can be assumed that, with the limited number of samples available to him, in 1835, he did not have much data to add to the properties already determined in Saint Petersburg and also mentioned in the note by Brewster the same year. It is possible that he had been informed about the crystallographic investigations made by Gustav Rose in Berlin.[87] Nordenskiöld had known both Rose brothers since 1819 when they had spent about a year working together in the laboratory of Berzelius in Stockholm.[88] Obviously, the most interesting point for

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[79]   Nordenskiold (1857)
[80]   Berzelius (1836); see also section 3.2.
[81]   Refer to the correspondence between Nordenskiöld and Berzelius, section 3.2.
[82]   Rose (1839a) and (1839b).
[83]   Letters from Perovskii to Nordenskiöld (April 1833 and May? 1833); correspondence between Berzelius and Nordenskiöld; see section 3.2.
[84]   See section 3.6.
[85]   Golynskaya and Svirina (1997).
[86]   Drafts of letters to Berzelius and Brewster, both 1834; correspondence between Berzelius and Nordenskiöld, section 3.2.
[87]   Some letters of Gustav Rose's brother Heinrich, who was also Professor at Berlin university document this close contact.

Nordenskiöld was the evaluation of the colour change in alexandrite, but proving the presence of vanadium as a possible colour-causing element was difficult (correspondence between Berzelius and Nordenskiöld). Eventually chromium was detected in chrysoberyl from the Urals in 1839 and a quantitative analysis for chromium in Uralian chrysoberyl was published in 1842.[89]

In 1839 the Krasnobolotsky Mine was intensely worked, and between 1839 and 1840, the best alexandrite crystal groups ever found in Russia, together with facetable material were unearthed. Thus, Perovskii and possibly other members of the Imperial Cabinet with an interest in mineralogy (the list of honorary members of the Society in the 1842 volume contains numerous Ministers of the Emperor's Cabinet and many members of the highest rank within the Saint Petersburg administration and scientific community) may have concluded that to name the new chrysoberyl variety in honour of the Tsarevich was desirable and possible. Although Kokovin, as finder and discoverer of alexandrite, should have had some association with the naming process, his disgrace, having been accused of stealing emeralds from the Emperor's property, made this impossible.

Between 1837 and 1841 Nordenskiöld and Berzelius still used both the terms cymophane and chrysoberyl in their correspondence. Thus, although we have no document concerned with the naming of alexandrite before the 1842 publication, it is possible that Perovskii and Nordenskiöld discussed this in the early 1840s. However the detailed roles of both Perovskii and Nordenskiöld, who had suggested the name alexandrite in honour of the Tsarevich, are still not clear. No direct documents are available to the present author that would describe any of these details or circumstances.

Letter No. 118 of the Söderbaum edition was written by Nordenskiöld to Berzelius in Saint Petersburg, dated April 23rd 1842, just before leaving. This might indicate that Nordenskiöld was in Saint Petersburg at the time the 25th anniversary volume manuscript was prepared (it was passed by the censor on April 17th 1842) and explain why there is no written communication about any arrangement or suggestion for the naming of alexandrite. All suggestions and arrangements could have been done ver-

bally with no written correspondence necessary. In letter No. 122, August 1842, Nordenskiöld informs Berzelius that he was awarded the Swedish Order of the North Star and that he expected to receive 5000 roubles in silver directly from the Tsar for one of his discoveries on improvements in iron metallurgy. These very personal letters to his close friend Berzelius show that Nordenskiöld also kept him informed on non-scientific news, but no letters in the Söderbaum collection mention the naming of alexandrite.

From the correspondence between Nordenskiöld and Berzelius we conclude and the draft of a letter to Brewster verifies that Nordenskiöld always considered Uralian chrysoberyl to be a gem mineral with extraordinary properties, especially to the colour-change effect between daylight and incandescent light. It is therefore possible that his suggestion for the naming of alexandrite was made without any prompting from high ranking members of the Imperial Cabinet. It is, however, almost impossible to assume that his suggestion was passed by the censor in April 1842 and published without having been previously approved, at least verbally, by members of the Imperial Cabinet or even by the Tsar himself.

In the most detailed biographies of Nordenskiöld available to the author, published by his colleagues and friends only a few years after his death in 1866,[90] only mention is made that he described some new minerals from the Urals. There is no mention of either the naming of alexandrite or of his close cooperation with Perovskii. Nordenskiöld had serious problems to face in the later years of his life. Because of political activities, his son Adolf Erik (Nils) Nordenskiöld (1832–1901) was forced to leave Finland in 1857, at that time part of the Russian Empire, and to live as an exile in Sweden. Additionally Nordenskiöld's position as Superintendent of the Mining Board in Helsinki was cancelled. He sold his beloved mineral collection to the Saint Petersburg Mining Institute Museum, most probably because of financial problems.[91] Under these circumstances the naming of alexandrite was not a topic intensely discussed among his close friends in Helsinki in the 1860s nor was it a matter that he was proud of and would have wanted documented.

88   Eichwald (1870); Golynskaya and Svirina (1997).
89   Rose (1839b); Awdejew (1842).
90   Arppe (1867); von Eichwald (1870).
91   Golynskaya and Svirina (1997).

3.5 Developments in the late 19th century

In a special volume celebrating the 50th anniversary of the Russian Imperial Mineralogical Society in 1867, there is an article by von Lawrow describing the mineralogical achievements of Franz von Wörth. In it are summarized the minerals von Wörth had examined and new discoveries resulting from his scientific work. It is correctly reported that he obtained his first crystals, of what was later to be known as alexandrite, from Perovskii in 1833 and that he determined chromium as the cause of colour.

By contrast many variations of these facts and of the details from the 1842 volume appear in the literature and especially on the internet. It is not possible to determine fact from fiction from these unsubstantiated accounts. Many of these modern variations of the true story are based on a novel by Nikolai Semyonovich Leskov, entitled "The Alexandrite", written in 1884 three years after the assassination of Tsar Alexander II (**Fig. 3.33**). In this mystic novel Leskov describes the colour change and properties of this gemstone that is dedicated to the late Tsar Alexander II. From original Russian literature sources giving details of the naming of the gemstone, Leskov quotes as follows (translated from Russian): "*The name was given to the gemstone because of its discovery on April 17th 1834, the day on which the later Emperor Alexander II came of age. The name was given by the Finnish mineralogist Nordenskiöld, because he (Nordenskiöld!!) found the gemstone at this day in the gemstone mines of the Urals at the river Tokovaya*". The colour change of alexandrite "green by day, red at night" was also associated with Alexander's life: green morning – full of hope, and red evening – the colour of blood and a symbol for the end of the Russian monarchy.

Before he wrote this novel Leskov consulted his friend Mikhail Pylyaev, who had already published a book on gemstones, about the mineralogical facts.[92] The 1st (1877) and 2nd (1888) editions of this textbook were published before and after the assassination of Tsar Alexander II in 1881. From these we learn that Nordenskiöld who had discovered the precious gemstone on the day of the coming of age of the Emperor on April 17th 1834 [93] named it alexandrite after Tsar Alexander II. It becomes apparent that the errors perpetuated by Koksharov in 1862 were modified in the late 1870s and Nordenskiöld had become the discoverer and finder of alexandrite.

More interestingly, the 2nd edition of Pylyaev's gemmological textbook mentions that alexandrites from Sri Lanka had been available on the market for seven years.[94] This indicates that alexandrite in antique jewellery dating from the last two decades of the 19th century could be of Sri Lankan origin and that samples collected by museums or by private individuals after 1880 might also be Sri Lankan and should be re-examined with this in mind.

Fig. 3.33 Portrait of Tsar Alexander II (1818–1881), Emperor from 1855. By an unknown artist, circa 1865. Portrait on display in the Hermitage Museum, Saint Petersburg. Photograph by K. Schmetzer.

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[92] McLean (1977).
[93] See also the reprint of the 2nd Edition, published in 1990.
[94] In the 1st Edition, alexandrites from Sri Lanka were not mentioned.

3.6 Alexandrite or diaphanite?

In addition to the stories by Leskov and Pylyaev further fabrications followed and in this way Nordenskiöld becomes credited with examining and identifying the first samples of alexandrite. Nordenskiöld is also mentioned for suggesting the name diaphanite for the new chrysoberyl variety. This name is similar to the mineral diphanite already mentioned[95] as occurring with other minerals associated with chrysoberyl and alexandrite in the Uralian emerald deposits.

A further literature search revealed that diphanite was a name given by Nordenskiöld to a mica found in a rock sample from one of the emerald deposits in the Urals.[96] This sample had been sent to him by Perovskii and the mica was named diphanite due to the fact that it changes in appearance when viewed from different directions.

The name is given as diaphanite[97] in a few 19th century documents that reviewed Nordenskiöld's description of the new silicate mineral. Later it was established that diphanite is identical to margarite, a mica frequently found in the mineral assemblages containing alexandrite and emerald in the Uralian deposits. Diphanite is now accepted as a synonym for margarite.[98] It seems unlikely that the eminent mineralogist Nordenskiöld would have suggested an identical or almost identical name for both the new chrysoberyl variety and for a variety of mica that occurs in the same mineral assemblage. Finally, the names diphanite and diaphanite are not found in any of the documents from the 1830s[99] dealing with colour-change chrysoberyl or cymophane from the Urals.

3.7 Use and production of alexandrite

The Krasnobolotsky Mine (Krasnobolotskoye deposit), situated in the southern part of the northwest to southeast-striking Uralian emerald belt, came into production in 1839. During 1839 and 1840 this mine supplied the most beautiful alexandrites as large crystals and crystal groups.[100] Trillings, with a maximum diameter of about 7.5 cm were found by the present author (KS). The most famous alexandrite crystal group from this locality and its history is described in section 3.3.2. Other alexandrites were unearthed in the Ostrovnoye deposit, also located in the southern belt, northwest of the Krasnobolotsky Mine.[101]

The largest faceted 19th century alexandrites examined by the present author are housed in the Natural History Museum, London (**Fig. 3.34**). These two gemstones, weighing 17.60 and 17.25 carats respectively, were acquired from Nicolas, Duke of Leuchtenberg, in 1867. Nicolas was the son of Maximilian von Leuchtenberg and nephew of the reigning Tsar Alexander II. Nicolas von Leuchtenberg was also President of the Russian Imperial Mineralogical Society from 1865 to 1890.[102]

Unfortunately there are no individual prices recorded for the two alexandrites, although the complete parcel of cut stones comprising four alexandrites, three phenakites, three sphenes, one sapphire, one rubellite and one topaz was purchased by the British Museum for the sum of £56 and 3 shillings in 1867.[103] This can be compared with the annual income of a general labourer or miner in England in the 1860s that was in the range of £50 to £60. Historical 19th century antique jewellery set with larger Russian alexandrites (**Fig. 3.35** and title figure of chapter 3) is amongst the most valuable.

It is extremely difficult to give production figures for gem quality alexandrite mined between 1833 and 1853, the date when most mining ceased until the mines were leased to the Anglo-French New Emeralds Company that operated from 1899 to 1916. In Leskov's 1884 novel[104] he describes faceted alexandrites as being extremely rare and very difficult to obtain from Russian jewellers. Foreign jewellers would have never have seen such stones. He also describes that special rings set with alexandrite

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[95] By Grewingk (1854) and von Kokscharow (1862 a,b).
[96] Nordenskiöld (1846, 1847).
[97] See, e.g. Berzelius (1848).
[98] See, e.g., Hey (1955).
[99] See section 3.2.
[100] Fersman (1929); Kozlov (2005); Bukanov (2006).
[101] Fersman (1929).
[102] Refer section 3.3.1.
[103] Personal communication from A. Hart (2009).
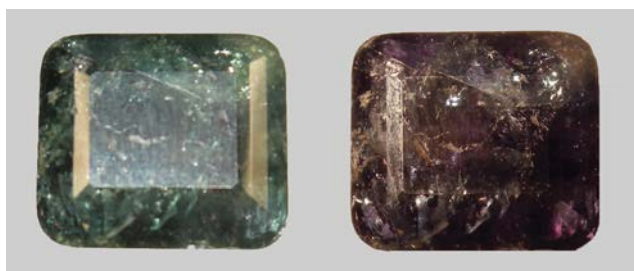[104] Refer section 3.5.

Fig. 3.34 This faceted Russian alexandrite of 17.25 ct is one of the largest cut 19th century historical Russian alexandrites examined by the author (KS). The sample was acquired in 1867 by the British Museum, London, from Duke Nicolas von Leuchtenberg and was later transferred to the Natural History Museum (see chapter 3 section 3.3.1). Photograph by K. Schmetzer.

were produced in memory of the late Tsar, who was assassinated in Saint Petersburg in 1881. A ring that Leskov wore at that time is described as set with an alexandrite and two smaller diamonds. These gems symbolized Alexander's two major achievements; the liberation of the Russian peasants from serfdom and the reformation of the judicial system.

The use of Russian alexandrite and its rarity outside Russia are confirmed by Bauer[105] who states…. "*The, at first, exclusively Russian occurrence of the stone and the fact that it combines the national military colours, green and red, gives it a peculiar value in the eyes of the Russians, by whom it is worn with great pride.*" Most alexandrite crystals are heavily fractured and facet grade material of good quality is extremely rare.

Published information on the use of alexandrite by the Imperial family is difficult to obtain.

In 1960 Twining mentions that the collection of precious stones of Catherine the Great (1729–1796) contained some alexandrites. However, this is not possible, as she lived in 18th century before the recorded discovery of the first alexandrite in the 1830s. The web site royal-magazin.de shows a portrait of Empress Alexandra Feodorovna,[106] the wife of Tsar Nicolas I and mother of Alexander II, wearing different items of jewellery containing green and red gemstones and is entitled "Alexandrite Parure of Empress Alexandra Feodorovna…" It was concluded that the artist, Franz Krüger, wanted to show

the colour change of alexandrite in this painting, but unfortunately no written proof of this idea exists.[107] A search for the original painting (**Fig. 3.36**) almost certainly excluded this possibility. A photograph of this portrait is available on at least two websites on the internet.[108] In both, the caption indicates a painting by Franz Krüger circa 1830, a date definitely too early for alexandrite jewellery. The first reference states that the original portrait is housed in the Muzej Istorii Moskvy (Historical Museum), Moscow. From a gemmological perspective it is possible that the gemstones depicted are emerald and ruby or emerald and spinel.

The huge four volume catalogue entitled "Russia's treasure of diamonds and precious stones" published under the supervision of A.E. Fersman between 1925 and 1926 comments that Russia's diamond treasure comprised the best portion of the state-owned jewellery and regalia, formerly the property of the Tsars. This catalogue was originally produced at the request of the communist government in order to sell the various items by auction. The catalogue, published in Russian, English and French was later withdrawn and is not available in Russian public libraries.[109] In his search, the present author consulted an English edition available at the Bavarian State Library in Munich. In total 406 items are described in great detail all with photographs and all gemstones are identified and listed. There are different items of jewellery set with Russian emeralds, the first dated at 1835, but there are no items of jewellery containing alexandrite.

There are, however, three interesting notes found in the general description that emphasises the fact that no Russian alexandrite was available in the 1920s. These are:

Page 15 …"*There is also a remarkable collection of … topazes, alexandrites, aquamarines, beryls …*"

Page 18 …"*Something ought to be said here in connection with our own native-stones. When and how disappeared from the Treasure the purple amethyst gleaming at night like red fire for the search of which Catherine II sent thousands of miners to the Ouralian borders? Where are now the bewitching cherry-coloured sherls, dark under artificial light (worn by our courtiers as Badges of Honour)? Also missing our iridescent emeralds and the celebrated alexandrites once so abundant in the imperial caskets! No explanation of this*

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[105] Bauer (1896, 1904); also Schrauf (1869).
[106] For a detailed biography, Grimm (1866),
[107] Personal communication from Ursula Butschal (2007, 2008).
[108] Bildarchiv Preussischer Kulturbesitz, bpk No. 00019408; and "Royal Family Imperial Style".
[109] Refer to "Russian imperial Diamond necklace expected to fetch US$2 Million".

Fig. 3.35 Antique diamond brooch set with an alexandrite, circa 1860 (top) and the same faceted alexandrite that is shown in both daylight and incandescent light (bottom). The sample was determined as alexandrite originating from Russia by the Gübelin Gem Lab, Lucerne, Switzerland. This unmounted alexandrite weighs 7.85 ct. Photograph of the brooch (top) by courtesy of Sotheby's Hong Kong. Photographs of the faceted alexandrite (bottom) by courtesy of the Gübelin Gem Lab, Lucerne.

loss has ever been given although one may suppose that our last tsars, too ready to despise Russian stones gave them away as souvenirs."

Page 22 … "… many other fine stones: pink brazilian topazes, deep-green Ceylan-alexandrites (red at night) – morning's green, evening's red said Leskov – aquamarines …"

Finally, there is some information contained in the publication "Treasures Hidden by the Imperial Family in Tobolsk" that describes a list of 154 items of jewellery that were still in the possession of the Imperial family during their imprisonment in Tobolsk after the Revolution. Item 80 describes a … "*gold cross with alexandrite*".

From these references it may be concluded that the Imperial family possessed alexandrite jewellery but no Russian alexandrite jewellery or unmounted stones were available after the Revolution. The faceted alexandrites that remained in the treasure were from Sri Lanka. The present author does not know whether any alexandrite jewellery was amongst the numerous items sold by the Imperial family after the Russian-Japanese war in 1906 for a fraction of their present value.[110]

Twining only mentions one instance where alexandrite was used in other European Regalia. This was in the Norwegian crown, made after the separation from

Denmark in 1814 and first used at the 1818 coronation. However, this date is definitely too early for alexandrite to have been used in jewellery. In addition, a detailed description of the Norwegian Regalia[111] does not mention alexandrite among the various gemstones in the Crown. Thus Twining's note is possibly incorrect.

Fig. 3.36 Portrait of Empress Alexandra Feodorovna (1798–1860), wife of Tsar Nicolas I and mother of Tsar Alexander II, shown bejewelled; wearing a parure comprising kokoshnik, matching bracelets, corsage elements, ear pendants and a pearl necklace. Portrait by Franz Krüger, circa 1830, Muzej Istorii Moskvy, Moscow, Russia (possibly painted during Krüger's stay in Saint Petersburg from June 1832 to May 1833). The gemstones were designated alexandrites, but the early date of the painting precludes this. There is a possibility that the gemstones were re-coloured at a later date. Several versions and copies of this painting are in existence. One version kept in the Hermitage Museum, Moscow, and assigned to A. Maliukov (1836) shows all the gemstones painted in a unique green colour. For reference see Alexandra Feodorovna (Charlotte of Prussia). Copyright bpk Bildagentur für Kunst, Kultur und Geschichte, Berlin. Photograph by Alfredo Dagli Orti and reproduced with permission.

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[110] Twining (1960).
[111] Risåsen (2006).
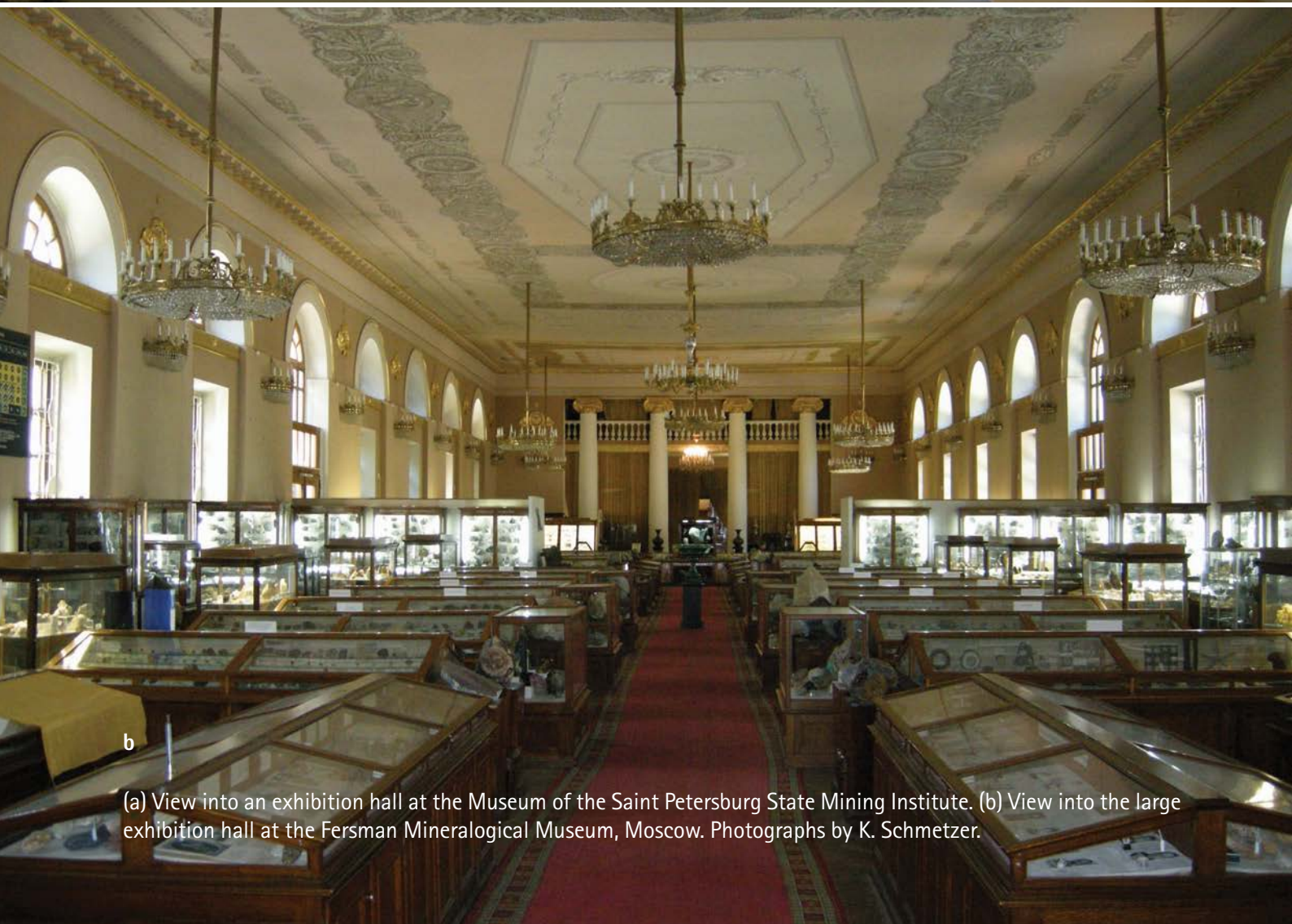
(a) View into an exhibition hall at the Museum of the Saint Petersburg State Mining Institute. (b) View into the large exhibition hall at the Fersman Mineralogical Museum, Moscow. Photographs by K. Schmetzer.

Russian alexandrites in mineralogical museums and in the trade

Karl Schmetzer

Chapters 5 and 6 of this book are based on the examination of the morphology of about 400 alexandrite crystals and crystal groups from both public (museum) and private collections. In addition about 20 light green, yellowish green and yellow green chrysoberyl crystals and crystal groups in matrix were examined. The mineral assemblages of 55 crystals and crystal groups, mostly the micaceous matrix and some associated minerals, were examined by micro Raman spectroscopy. Ten mica samples were chemically characterized by electron microprobe or by an electron microscope (SEM-EDX).

Further characterization of gem-quality samples by microscope examination included:

▶ 30 transparent rough crystals with no matrix
▶ 120 faceted alexandrites and colour-change green to yellowish green chrysoberyls
▶ 21 cabochon cut alexandrites and chrysoberyls
▶ 10 faceted chrysoberyls that did not show a distinct colour change between daylight and incandescent light.

Mineral inclusions in 15 of the faceted samples were identified by Raman spectroscopy.

The study commenced with 17 transparent gem quality crystals produced from the Malysheva Mine after the year 2000 and progressed to the examination of a limited number of both gem and non-gem quality crystals and crystal groups in matrix loaned by private collectors in Germany. The latter samples had been purchased after 1990 and probably most were excavated from the Malysheva Mine in the second half of the 20th century.

Following this preliminary study, it was decided to expand the research project to include museum specimens and commercially available faceted and rough samples. One of the authors (KS) was permitted to study the complete inventories of eight collections in order to get an overview of alexandrite samples in museums since the 1830s. This included all samples on public display as well as those in stock. These eight collections are housed in museums in Saint Petersburg and Moscow, Russia (Nos. 1 to 4); Vienna, Austria (No. 5); London, England (No. 6); and Munich and Berlin, Germany (Nos. 7 and 8).

1. Museum of the Saint Petersburg State Mining Institute and Technical University, Saint Petersburg, Russia. Established 1773.
2. Mineralogical Museum of Saint Petersburg State University, Saint Petersburg, Russia. Established 1785.
3. Fersman Mineralogical Museum, Moscow, Russia. Founded in 1716 as the Mineral Cabinet of the Kunstkammer in Saint Petersburg and moved to Moscow in 1934.
4. Vernadsky State Geological Museum, Moscow, Russia. Established 1755.
5. Naturhistorisches Museum (Natural History Museum), Vienna, Austria. Established 1750.
6. Natural History Museum, London, England. Originally established as the British Museum in 1753.
7. Mineralogische Staatssammlung (Bavarian State Collection for Mineralogy), Munich, Germany. Established 1803.
8. Museum für Naturkunde (Museum of Natural History), Berlin, Germany. Established 1770.

The same general problems were encountered in all the museum collections:

All samples had well preserved labels, inventory numbers or even individual filing-cards that clearly document when and how the alexandrite specimens came into the collection. This provided information on details such as the origin of the sample, the date on which it was purchased or donated to the museum by a private collector, mineral dealer or Russian mining company. However the complete history of the sample prior to its acquisition by the museum is usually unknown.

Fig. 4.1 View into an exhibition room at the Museum of the Saint Petersburg State Mining Institute. The showcase contains malachite and is part of the museum furniture dating back to the late 18th century. In other parts of the museum, display furniture dates back to the first part of the 19th century (Kolomensky and Fainstain, 1994). Photograph by K. Schmetzer.

Samples were kept in one or more private collections and over fifty years could pass between the discovery of a specific sample and the time it came into a museum collection. One notable example is the famous crystal group, described and drawn by Koksharov in 1862 that came to the Fersman museum in 1913 as part of the Kochubei collection.[1] Samples were acquired by Russian museums in the 20th century from complete collections, such as Carl Fabergé's gemstone collection. In these instances it could be established from the former owner that the samples are from the 19th century and had been kept for several years in a private collection.

The two largest collections of 19th century samples are found in the museum of the Mining Institute in Saint Petersburg and the Fersman Museum in Moscow (**Fig. 4.1** and title figures of chapter 4). The oldest crystal groups and individual crystals kept in the Mining Institute were purchased from Count Perovskii. A large group of 19th century samples in the Fersman museum (**Fig. 4.2**) was part of Prince Kochubei's collection and came into the museum in 1913. Most of these samples originated from Perovskii's private collection and were purchased from Kochubei after his death. From this history it can be deduced that many alexandrite samples from these early years passed into Perovskii's hands as a result of his

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[1]   Refer to title figure of chapter 6; for the history of the Kochubei collection see chapter 3, section 3.3.2.

Fig. 4.2 Some alexandrite specimens on display in the Fersman Mineralogical Museum, Moscow. Photograph by K. Schmetzer.

positions as Vice-President of the Appanage Department (1831–1841) and Minister of the Interior (1841–1852). However, the fine line that divides Perovskii's activities as a private collector from those of his official duties is not always clear.

The precise locations of samples originating within the Tokovaya mining region were seldom recorded (**Fig. 2.4**). Most samples are labelled "Tokovaya", "Urals" or even "Ekaterinburg", with no further details because they were not considered to be of interest at that time. For example, the first inventory of the Mining Institute in Saint Petersburg,[2] lists 37 chrysoberyl crystals from the emerald deposits (**Fig. 4.3**) with no further details on specific localities. In some cases, the specific location of a particular sample can only be surmised. As an example, if a complete collection of samples was given to a museum by the Directors of the Malysheva Mining Company in 1980, we may conclude that most of

Fig. 4.3 Some alexandrite specimens on display in the Museum of the Saint Petersburg State Mining Institute. Photograph by K. Schmetzer.

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[2] Nefedev (1871).

Fig. 4.4 This series of Russian alexandrite specimens from the Rolf Goerlitz Company, Idar-Oberstein, Germany was examined in this present study. The variability of colour in both daylight (above) and incandescent light (below) is demonstrated. Samples from left to right are from 1.61 ct to 7.73 ct, respectively. Photographs by K. Schmetzer.

these samples were collected from the Malysheva Mine after 1950. Another example is in the Vernadsky Museum that now houses Yu. Kozlov's collection, samples of which are pictured in his alexandrite books.[3] Most of these samples, collected between 1968 and 1998, originate from the Malysheva Mine, but there may be a few "older" alexandrites from other locations in the Uralian mining area that found their way into the Kozlov collection.

Further alexandrites from the Urals as crystals, crystal groups or samples in matrix were loaned from three sources. Two German collectors, Christian Weise from Munich and Frank-Jürgen Schupp from Pforzheim, had purchased their samples from Russian dealers since 1990 and the third group of samples, mined by the Tsar Emerald Company between 2006 and 2007 was obtained from Warren Boyd, Oakville, Ontario, Canada.

Unfortunately, only a small number of 19th or early 20th century faceted alexandrites are housed in mineralogical museums. The Munich Museum contains one alexandrite from the Leuchtenberg collection that is dated before 1850 (**Fig. 3.18**).[4] In Vienna, two faceted Russian stones, one an extraordinarily large stone of 12.8 ct,[5] were purchased in 1890. The Fersman Museum in Moscow has on display two faceted stones with excellent colour change. These have been in the museum since 1925 and originate from the private collection of Carl Fabergé which implies that they are also from the 19th century. The Natural History Museum in London holds two extraordinarily large stones weighing 17.60 and 17.25 ct purchased from Nicolas, Duke of Leuchtenberg, the son of Maximilian von Leuchtenberg in 1867.[6] In addition, there is a smaller sample in the London collection purchased in 1882. The Berlin

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[3]　See Kozlov (2003, 2005).
[4]　For the history of the Leuchtenberg collection see chapter 3, section 3.3.1.
[5]　Title figure of chapter 3.
[6]　Refer to chapter 3, sections 3.3.1 and 3.7.

Fig. 4.5 Faceted Russian alexandrite showing excellent colour change from bluish green in daylight to purple in incandescent light. This 1.08 ct sample was supplied by the Tsar Emerald Company and R. T. Boyd Limited, Oakville, Ontario, Canada and originated from the Malysheva Mine, Russia in the 21st century. Photograph by K. Schmetzer.

collection holds three faceted stones purchased in the 1920s.

Using the author's own immersion microscope, an examination was completed on some of the stones in the Munich, Berlin and Vienna collections.

In addition to the limited number of faceted alexandrites with some historical background mentioned above, seven Russian stones from a private German collection, in existence since the early 1920s, were examined. Given the circumstances under which these samples were acquired, they are most probably older than the 1920s.

At the beginning of the study, we included several samples traded as Russian alexandrite, but most of these were excluded because their origin and history were not clearly proven. Consequently, in general only faceted stones available through three different trade sources were used. Two were dealers in Germany who either bought the rough material directly from Ekaterinburg or Malysheva in the Urals or obtained it in Germany and personally faceted the material. If faceted stones were also bought from the same suppliers, they were accepted for the present research project providing original rough material was available for study. Most alexandrites (**Fig. 4.4**) from these two dealers originated from the Malysheva Mine and were mined after 1970 however, some of them may be older and we cannot completely dismiss the possibility that there might also be a few 19th century stones within this group.

The third group of faceted stones (**Fig. 4.5**) are definitely from the Malysheva Mine and were produced by the Canadian-based Tsar Emerald Company after 2000. The faceted stones were cut from samples produced during this time period.

The Natural History Museum in London hosts two alexandrite trillings from the Koksharov collection. The different faces of the individuals are labelled with Miller indices, shown in different colours, twinning and twin boundaries can be easily recognized using this system. (a) The sample size is approximately 3.5 x 4.5 cm. (b) The sample size is approximately 6.5 x 6.5 cm. Photographs by K. Schmetzer.

5 Morphology and twinning

Karl Schmetzer

In this book we designate the different individuals of a twin with I and II, the individuals of a cyclic twin (trilling) with I, II, and III. The same faces on different individuals of a twin or trilling are designated with the number of the crystal. Thus the **o1**, **o2** or **a1**, **a2**, **a3** indicate the **o** or **a** faces of the first, second or third individual of a twin or trilling. Symmetry equivalent faces of one individual crystal are designated as follows, **o1** and **o1'**, **w1** and **w1'**, or **i1** and **i1'**. Furthermore, we have distinguished between the **o** faces forming an angle of 139.79° (designated as **o1** and **o1'** adjacent), two **o** faces forming an angle of 86.16° (designated as **o1** and **o1'** opposite) and two **o** faces forming an angle of 72.34° (designated as **o1** and **o1'** diagonal) (**Fig. 5.1** and **Table 2**).

5.1 Review of the literature

The first description of alexandrite crystals from the Urals was published by Gustav Rose.[1] He realized that most of his specimens occurred as repeatedly twinned crystals with pseudohexagonal dipyramidal habit. Rose prepared the first drawing of this type of alexandrite crystal and constructed a "theoretical" line drawing of a single crystal (**Fig. 3.3 a, b**). Both drawings were also published by von Pott in 1842. Koksharov[2] produced crystal drawings of two single crystals, two contact twins and eight multiple twinned pseudohexagonal crystals.[3] He also noted crystals with a second tabular habit and described most samples as pseudohexagonal twins. Single crystals are rare and only two simple contact twins consisting of two individuals were known at that time, one in each of Koksharov's and Kochubei's collections.[4] The discovery of another alexandrite twin in 1863 was noted;[5] this underlines the rarity of Uralian alexandrite twins discovered during the period 1830–1870.

Later, additional single crystals and twins were described by various authors.[6] The first overview on the morphology of Russian alexandrite and chrysoberyl from various localities was presented by Schrauf, who redrew some crystals and presented them in unique orientations. Goldschmidt, on the other hand, summarized the morphology of chrysoberyl and presented crystals in their original setting and orientation, i.e. as described in the different original publications.[7] The 32 Russian crystals described by Goldschmidt were also depicted, in the same orientation, in Kozlov's[8] recently published books on Uralian alexandrite. Zhernakov also used the crystal drawings as published by Koksharov without changes, but erroneously assigned one twin described by Klein to Koksharov.[9] Zhernakov also described the different habits of alexandrite trillings and used hexagonal crystal system terminology such as hexagonal bipyramid and hexagonal prism based on the pseudohexagonal habit of the samples.

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[1] Rose (1839b, 1842).

[2] Koksharov (1853a, 1862 a,b).

[3] Although rarely cited in scientific literature, the monograph of Koksharov (1862b) is the most detailed treatise on morphology and twinning in Russian alexandrite.

[4] The alexandrite twin from Koksharov's collection, drawn as Figure 10 in the "Atlas" (Koksharov 1853a) and in his alexandrite monograph (Koksharov 1862b) fits in morphology to a crystal from the Koksharov collection which is kept in the Natural History Museum London (see Fig. 5.7g).

[5] Protokoll der Sitzung am 26. Januar (1863).

[6] E.g. Klein (1869, 1871); Schrauf (1877); Cathrein (1882); Melczer (1900); Duparc and Sabot (1911).

[7] Schrauf (1877); Goldschmidt (1913).

[8] Kozlov (2003, 2005).

[9] Klein (1869); Zhernakov (2009).

Fig. 5.1 A single crystal of alexandrite shown in different clinographic projections; (A) view parallel to the a-axis, (B) view parallel to the b-axis and (C, D and E) show two views parallel to the c-axis. Adjacent **o** dipyramids form angles of 140° to each other, opposite **o** dipyramids form angles of 86° to each other and diagonal **o** dipyramids form angles of 72° to each other, all **o** dipyramids in green colour. Crystal drawings and artwork by K. Schmetzer.
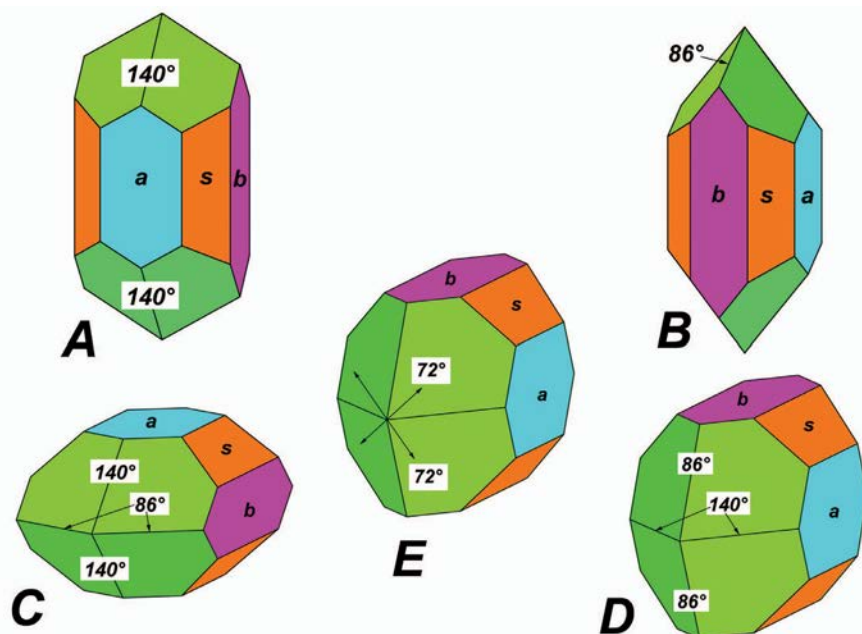
A unique elongated (columnar) alexandrite trilling in the Pelepenko collection is pictured twice,[10] but there is no record of any detailed research on this particular crystal habit.

Twinning of Russian alexandrite and chrysoberyl in general has been examined in detail by various authors.[11] Koksharov first assumed that two different twin laws might exist: penetration twinning on (011) and contact twinning on (031). Detailed goniometric measurements obtained later on samples from other occurrences excluded the first possibility. It is now generally accepted that both chrysoberyl and alexandrite are twinned on (031) and (0$\bar{3}$1) with both (031) and (0$\bar{3}$1) as twin and composition planes. It is also assumed, that both contact twins and penetration twins exist (**Fig. 5.2**).[12]

5.2 Morphology and twinning in Russian alexandrite in particular

The twinning of Russian alexandrite has already been described by Rose in the first scientific paper on the new gem material. The crystals most commonly described are cyclic twins or trillings, but crystals consisting of six independent chrysoberyl individuals are also mentioned in the literature. Single crystals or twins from the Tokovaya area are rare and an understanding of the morphology of the common Russian crystals requires an interpretation of their twinning formation.

At the time of the publication of the first comprehensive work on the morphology of Uralian alexandrites by Koksharov,[13] only two twinned and a few single crystals were available from this area. These crystals mainly displayed six different crystal forms: the two pinacoids **a** {100} and **b** {010}, the two prisms **i** {011} and **s** {120}, and the two dipyramids **o** {111} and **n** {121}. Later, prisms **m** {110} for single crystals and twins were frequently described in the literature. As a result of this current work, the dipyramid **w** {122} has been added as an additional crystal form frequently observed in crystals found from Malysheva Mine after 1945.

Russian chrysoberyl is described as consisting of either three interpenetrant single crystals (trillings) or six individuals that show repeated contact twinning (**Fig. 5.2**). The governing twin law reflection on (031) and (0$\bar{3}$1) is mentioned in mineralogical textbooks. Both

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[10]   Burlakov et al. (1997); Zhernakov (2009).

[11]   Koksharov (1862 a,b, 1865); Frischmann (1867); Schrauf (1877); Melczer (1900); Goldschmidt (1900); Goldschmidt and Preiswerk (1900); Liffa (1902).

[12]   See, e.g., Niggli (1927).
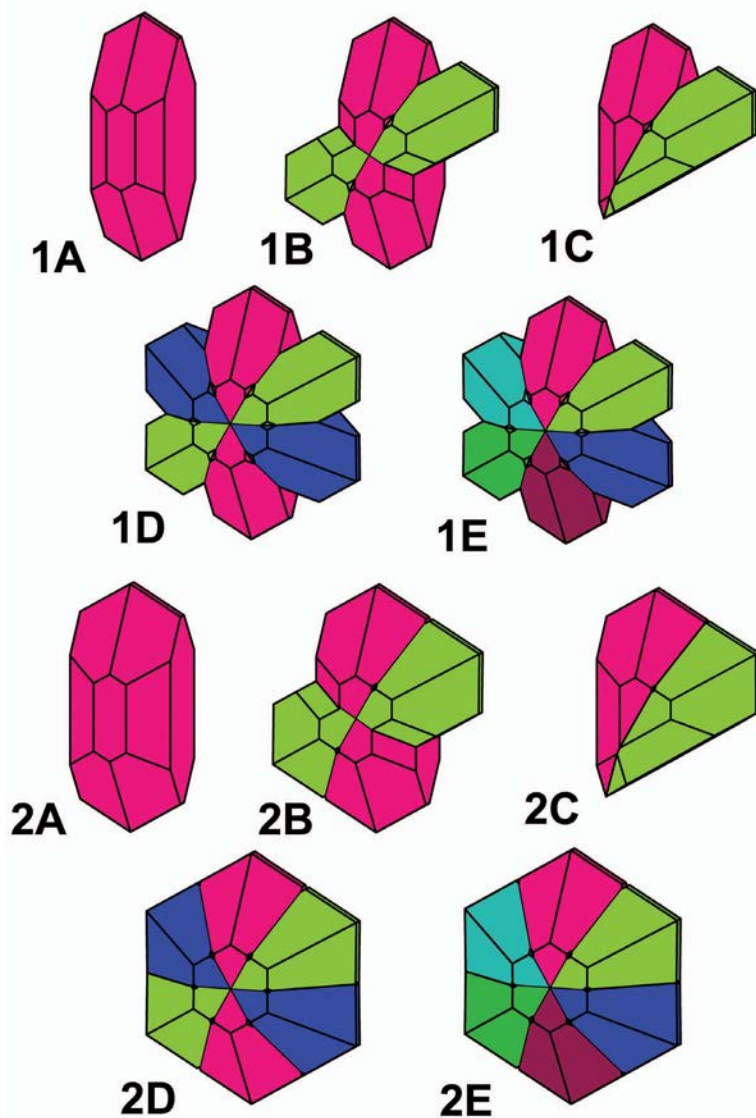
[13]   Koksharov (1853a, 1862 a,b).

Fig. 5.2 Different twin types in alexandrite. On the twin plane (031) two different single crystals (1A and 2A) are shown forming penetration twins (1B and 2B) or contact twins (1C and 2C). Cyclic twins consist of three penetration twins (1D and 2D) or six contact twins (1E and 2E). According to the relative sizes of different faces of the single crystals shown as (1A and 2A), the different types of twins show either distinct re-entrant angles (1B to 1E) or almost no re-entrant angles (2B to 2E). Crystal drawings and artwork by K. Schmetzer.

twin planes are also the composition planes of the crystals. The investigation of whether there are three penetration crystals or six contact twins requires exact goniometric measurements of well developed crystals. This is not in the scope of the present volume because the final description of the observed samples would not be different.

To understand the morphology of the Russian alexandrite crystals, it is helpful to consider an untwinned single crystal and its orientation in the repeatedly twinned trilling. In the left column of **Fig. 5.3** two different single crystals are each drawn in two orientations perpendicular to each other. In the central column, the orientation of these crystals in the transparent outline of the trilling is shown. In the right column, the complete trilling and the twin boundaries are drawn. From these drawings in the right column, it is evident that the samples can be de-

scribed as interpenetrant trillings or as crystals consisting of six individual contact twins, twinned by repeated reflection (**Fig. 5.2**).

However, it is significant that the angle between the c-axes of single individual crystals is almost exactly 60°, forming the complete pseudohexagonal habit of the trilling. In twinned individuals, the prisms **i** (011) and the dipyramids **o** (111) are almost parallel to each other with less than 0.5° deviation from 180°. Therefore the intergrown **i** or the **o** faces of two individual crystals form single plane faces in the cyclic twins. Thus, the twin boundaries on these plane faces are only occasionally observed as weak striations on the faces. However if the re-entrant angles are formed by the pinacoid **b** (010), the prism **s** (120), the dipyramid **n** (121) or by combinations of these faces, the twin boundaries (composition planes) are clearly seen.

Fig. 5.3 Formation of cyclic twins (trillings) in alexandrite. Two different single crystals (A and D) and trillings (C and F) are shown in different orientations in views parallel to the a-axis (upper rows) and perpendicular to the a-axis (lower rows). After reflection on (031) and (0$\bar{3}$1) the final trillings are formed (C and F). The intermediate drawings (B and E) show the full outlines of the final trillings and the orientations of the complete single crystals. According to the relative sizes of different faces of the single crystals (A and D), the cyclic twins show either distinct re-entrant angles (C) or almost no re-entrant angles (F). Crystal drawings and artwork by K. Schmetzer.
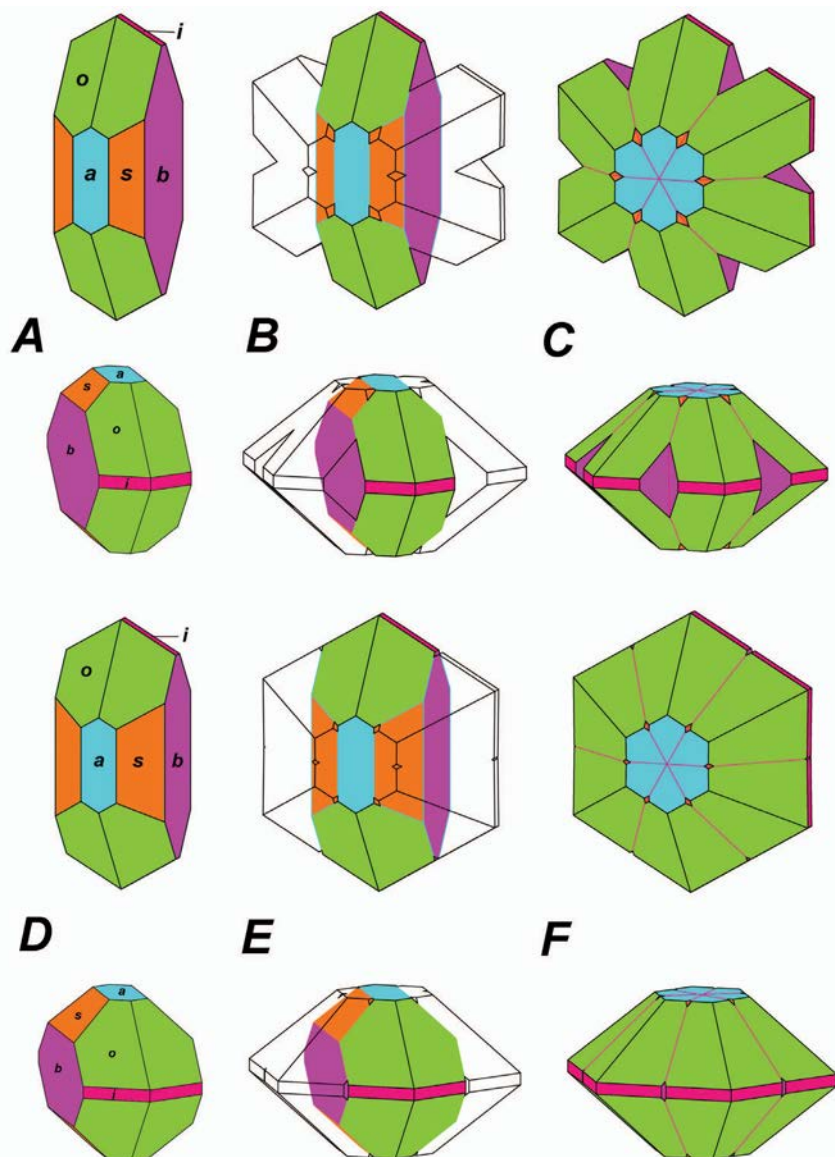

Fig. 5.4 Interpenetrant twin of alexandrite from Lake Manyara, Tanzania. A slice of a crystal was cut parallel to the **a** pinacoid (100) and perpendicular to the **b** pinacoid (010) and the **i** prism (011); the two individuals of the interpenetrant twin start in the centre at the origin of crystal growth (see schematic crystal drawing); just beyond the centre, a contact twin (marked by an arrow) is shown attached to the main individual. The length of the part of the twin shown in this image is 3.9 mm. Photograph by H.-J. Bernhardt.
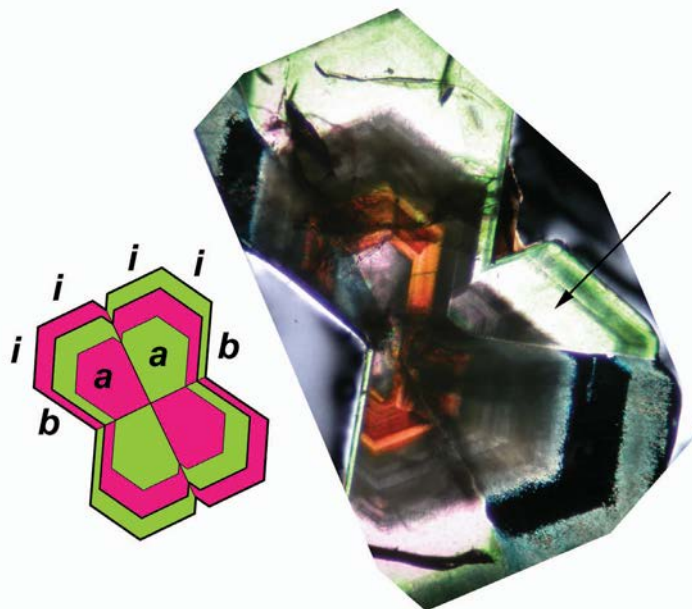
In the crystals shown in **Fig. 5.3 A, B and C** the sizes of the **b** and **s** face are selected relative to faces **a, o** and **i** in order to show large re-entrant **b** pinacoid faces and smaller re-entrant **s** prism faces. Similarly the crystals in **Fig. 5.3 D, E and F**, the relative sizes of the different faces were selected in order to show the formation of a trilling and with parallel intergrowth of undivided **i** and **o** faces, almost without re-entrant angles. The twin boundaries depicted on these trillings in the right column are not normally observed on these plane faces (see also **Fig. 5.2**).

A slice of a twin from Lake Manyara, Tanzania (**Fig. 5.4**), also demonstrates twinning in alexandrite. The sample is cut perpendicular to the a-axis and is parallel to the pinacoid face **a** (100). Growth zoning is parallel to both the pinacoid **b** (010) and the prism faces **i** (011) as well as the external crystal faces of this interpenetrant twin. This is extremely rare in Russian alexandrites.

5.2.1 Single crystals

About ten untwinned single crystals were studied, some as part of larger crystal groups (**Fig. 5.5 a–g**). The samples show all the combinations of the common forms observed in Uralian alexandrites, namely pinacoids **a** and **b**, prisms **m, s** and **i** as well as dipyramids **o** and **n**. The habit of the crystals can be described as prismatic (**Fig. 5.6 A to D**) or prismatic to dipyramidal (**Fig. 5.6 E, F**). The morphology is more or less consistent with the alexandrite crystals described by Koksharov and Cathrein.[14] Samples comparable to the single crystals drawn by Klein or by Duparc and Sabot were not seen.[15]

5.2.2 Single contact twins

Although it was sometimes difficult to decide if a specific crystal was a true contact twin or part of a broken trilling, we were able to examine about 20 twins that were complete crystals or at least showed evidence that the zone with the faces (hk0) including **a**, **m**, **s** and **b** was not broken (**Fig. 5.7 a–m**). In this zone, pronounced striations were commonly seen on the **m** and **s** prism faces. This is an indication that other prisms such as **u** (230) and **r** (130) are present in this zone[16] but the small size of these faces made confirmation of this impossible without precise measurements using an optical reflecting goniometer. Some of the crystals had no, or only very small, re-entrant

angles (**Fig. 5.6 G to J**), but others showed clear re-entrant angles formed by the pinacoid **b** (**Fig. 5.6 L to N**), occasionally in combination with the dipyramid **n** (**Fig. 5.6 K**). In samples with re-entrant angles, the pinacoid **a** was, in general, larger than in others and as a result the habit of these contact twins becomes more tabular.

Penetration twins as described by Cathrein (**Fig. 5.7 n**) were only rarely seen in the collections of the Mining Institute in Saint Petersburg, the Museum of Natural History in Vienna and the Museum für Naturkunde in Berlin. These samples consist of elongated crystals with composition planes at both ends.

5.2.3 Cyclic twins (trillings)

The majority of samples examined comprised pseudo-hexagonal cyclic twins (trillings) of variable habit: dipyramidal (three different types), tabular, equidimensional and columnar. An overview of habits, the faces present and their relative sizes is given in **Table 2**. The three different types with dipyramidal habit are subdivided according to the subordinate forms present: **a** (type 1), **a** and **b** (type 2) or **a**, **b**, and **i** (type 3). The maximum diameter of crystals examined in the different museums was 7.5 cm (**Fig. 3.22**); crystals up to a diameter of 9 cm, as reported in the literature, were not found.

Dipyramidal crystals, <u>type 1</u>, (**Fig. 5.8 a–j**) show variations in thickness and diameter and some show small re-entrant angles at their edges between two **o** dipyramids, formed by the pinacoid **b** or the dipyramid **n**. Re-entrant angles at the edges between the pinacoid **a** and the dipyramid **o** are seen when prism faces **s** (**Fig. 5.9 A to F**) and occasionally a small prism **i** are present (**Fig. 5.8 g, Fig. 5.9 C**). In contrast to these trillings with dipyramidal habit formed by large dipyramids **o**, crystals with tabular habit (**Fig. 5.10 a–h**) show smaller dipyramids **o** and larger pinacoids **a**. Most crystals of this tabular type also have distinct prism faces **i**, occasionally with re-entrant angles formed by smaller pinacoids **b** (**Fig. 5.9 G, H**). Crystals with this habit have been previously described by Koksharov, and Fersman mentioned that around 1000 crystals of this type were excavated from the Krasnobolotsky Mine and found their way into various mineralogical collections.[17]

[14] Koksharov (1853a, 1862 a,b); Cathrein (1882).
[15] Klein (1871); Duparc and Sabot (1911).
[16] As described by Melczer (1900).
[17] Koksharov (1853a, 1862); Fersman (1929).

Fig. 5.5 a–g Single crystals of chrysoberyl and alexandrite from the Tokovaya area, Urals, Russia: b, c, e, f and g are single crystals, a and d are crystal groups made up of single crystals. Specimen locations and sizes are: a) Fersman Museum, 2.5 x 3.5 cm; b) Natural History Museum, 1.7 x 3.4 cm; c) Museum für Naturkunde, 1 x 1.5 cm; d) Vernadsky Museum, 3 x 3.5 cm; e) Schupp collection, 0.8 x 2.0 cm; f) Vernadsky Museum, 2 x 2 cm; g) Fersman Museum, 2.5 x 3 cm. Photographs by K. Schmetzer.
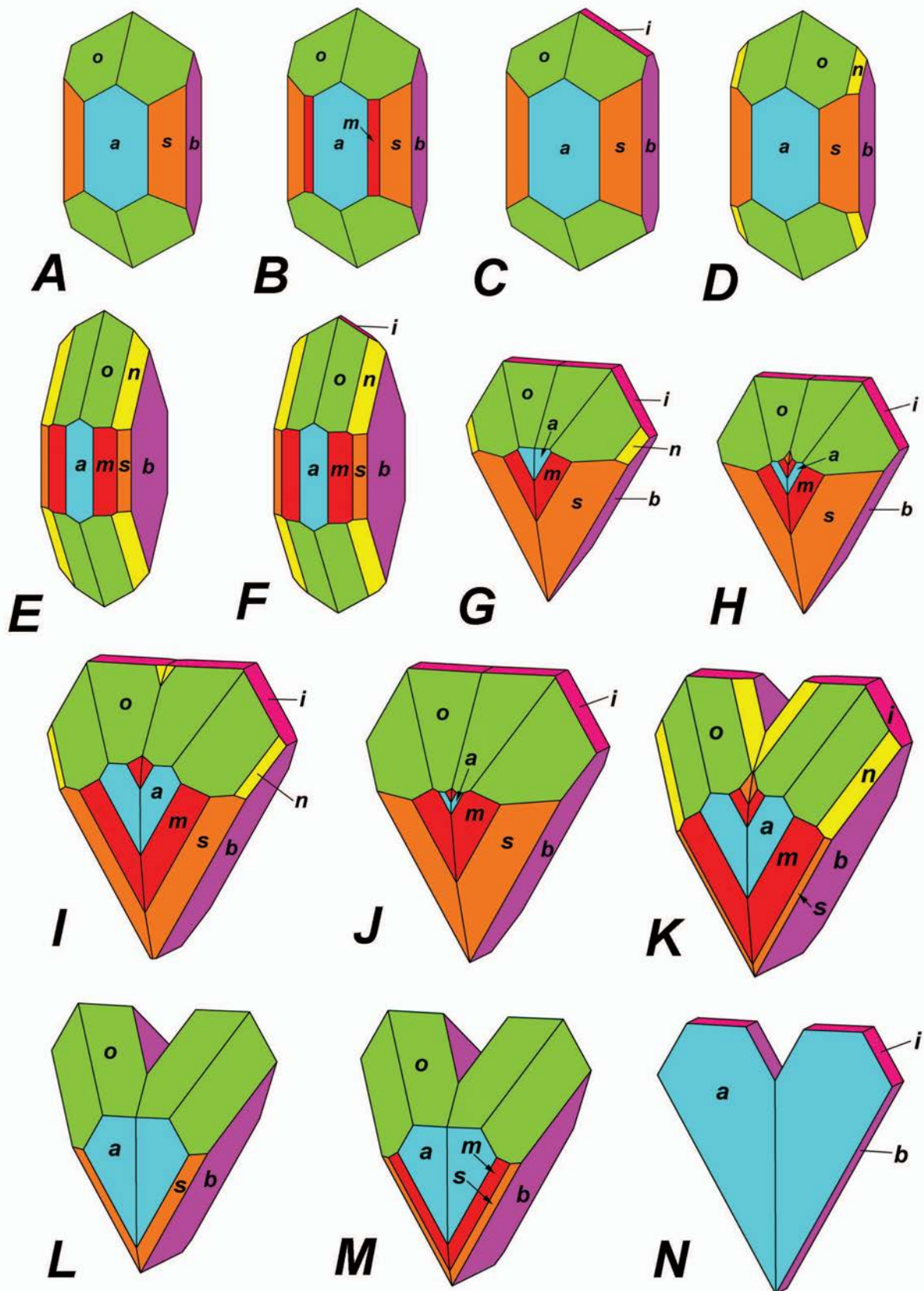
Fig. 5.6 Single crystals (A to F) and contact twins without re-entrant angles (G-J) and with re-entrant angles (K–N) of chrysoberyl and alexandrite from the Tokovaya area, Urals, Russia. Crystal drawings and artwork by K. Schmetzer.

Fig. 5.7/1 a to g Twinned alexandrite crystals from the Tokovaya area, Urals, Russia; a–g are contact twins without re-entrant angles, a and c are contact twins with matrix. Specimen locations and sizes are: a) Collection of Lorien Gems Company, Moscow, 3.2 x 3.3 cm; b) Museum für Naturkunde, 1.5 x 2.5 cm; c) Vernadsky Museum, 2.5 x 4 cm; d) Natural History Museum, 0.7 x 1.0 cm; e) Schupp collection, 1.1 x 1.2 cm; f) Natural History Museum, 0.5 x 0.7 cm; g) Natural History Museum, 0.6 x 0.9 cm (Koksharov collection). Photograph Fig. 5.7 a by Vitalii Repei, Moscow, all others by K. Schmetzer.
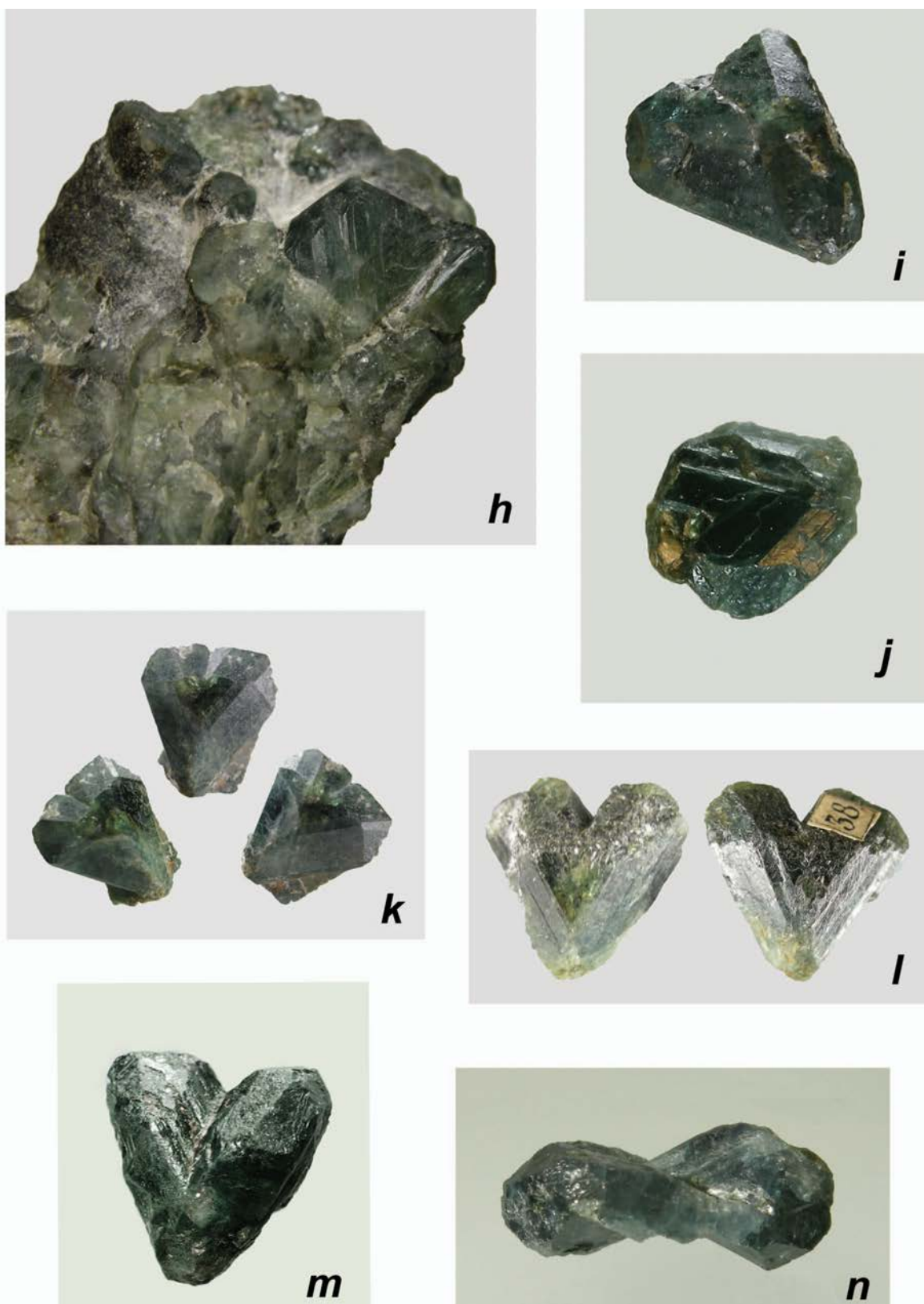
Fig. 5.7/2 h to n Twinned alexandrite crystals from the Tokovaya area, Urals, Russia; h–m are contact twins with re-entrant angles, h is a contact twin with matrix, n is an interpenetrant twin. Specimen locations and sizes are: h) Vernadsky Museum, 3.5 x 5 cm; i) Museum für Naturkunde, 1 x 1 cm; j) Schupp collection, 0.6 x 0.7 cm; k) Museum für Naturkunde, different views, 1.5 x 1.5 cm; l) Fersman Museum, different views, 1.3 x 1.3 cm; m) Schupp collection, 1 x 1 cm; n) Naturhistorisches Museum, 0.5 x 1.5 cm, No. F4315. Photographs by K. Schmetzer.
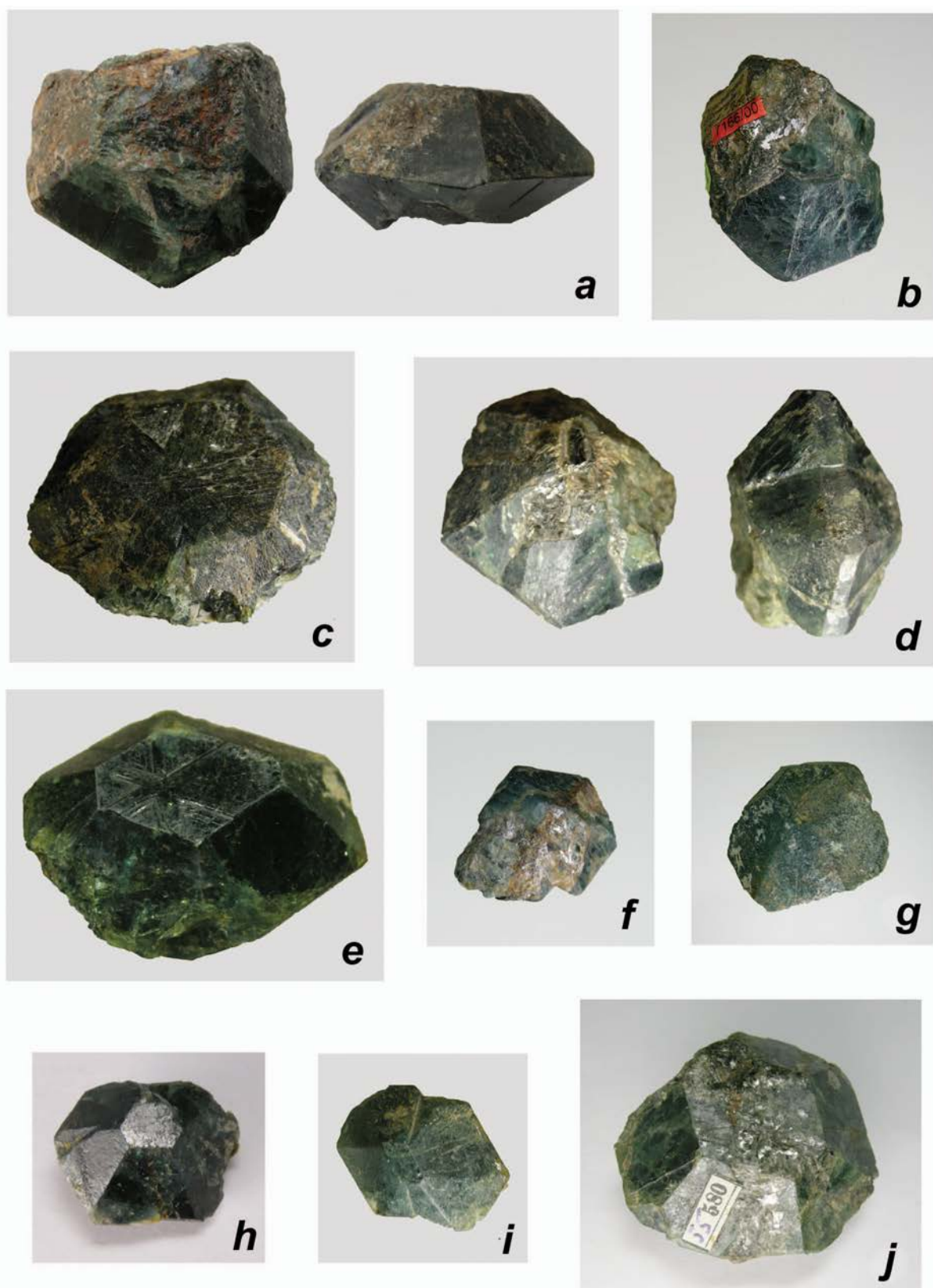
Fig. 5.8 a to j Cyclic twins (trillings) with dipyramidal habit (type 1) of alexandrite from the Tokovaya area, Urals, Russia. Specimen locations and sizes are: a) Mineralogische Staatssammlung, different views, 4.5 x 6 cm; b) Museum für Naturkunde, 2.5 x 3 cm; c) Fersman Museum, 4 x 5 cm; d) Fersman Museum, different views, 3.5 x 3.5 cm; e) Fersman Museum, 4 x 4 cm; f) Museum für Naturkunde, 2 x 2.5 cm; g) Museum für Naturkunde, 6.5 x 6.5 cm; h) Vernadsky Museum, 1.0 x 1.3 cm; i) Fersman Museum, 1.5 x 2 cm; j) Vernadsky Museum, 4 x 4 cm. Photographs by K. Schmetzer.
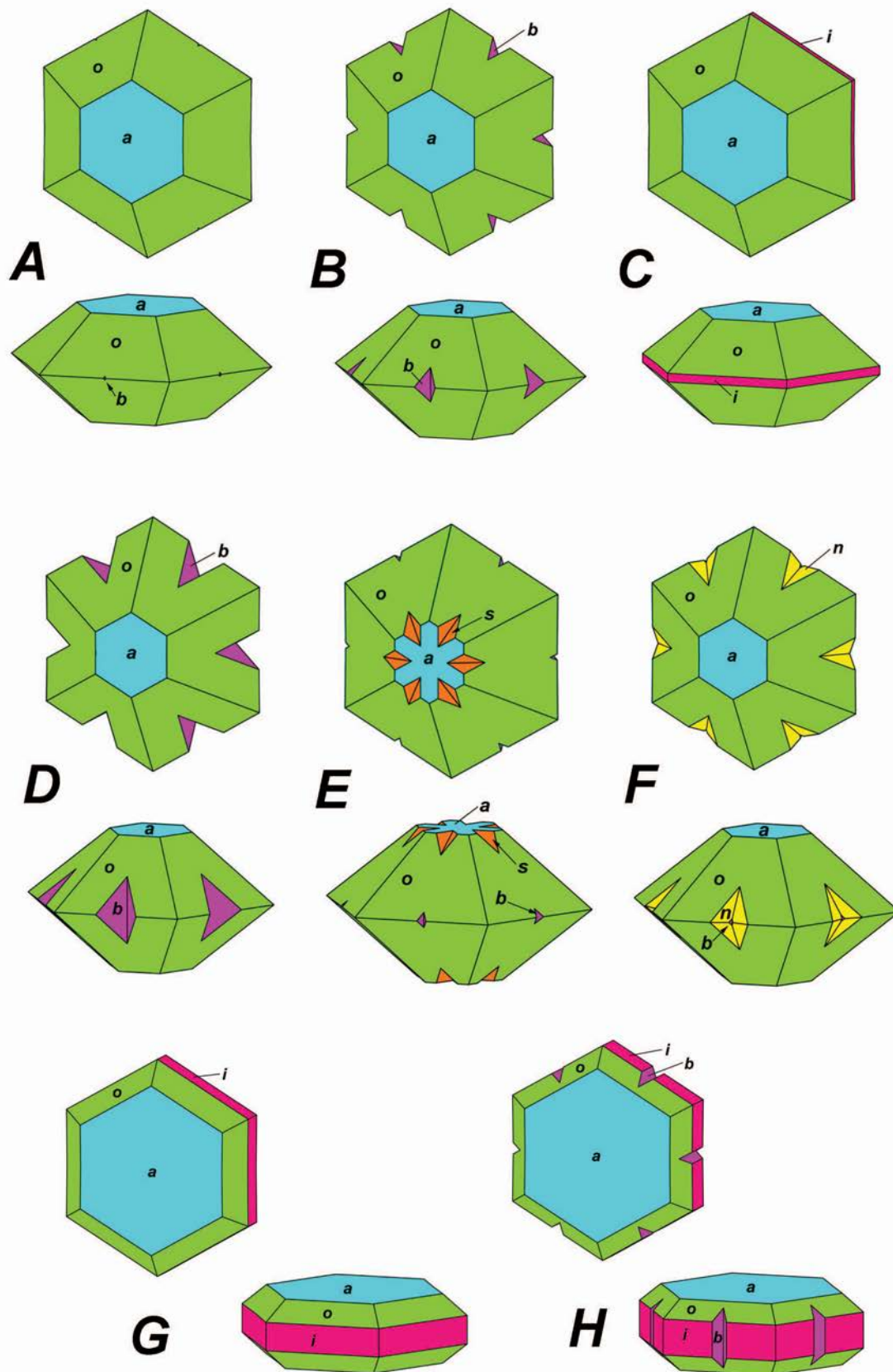
Fig. 5.9 Cyclic twins (trillings) with dipyramidal habit (type 1) (A to F) and cyclic twins (trillings) with tabular habit (G and H) of chrysoberyl and alexandrite from the Tokovaya area, Urals, Russia; views parallel to the a–axis (upper rows) and perpendicular to the a–axis (lower rows). Crystal drawings and artwork by K. Schmetzer.
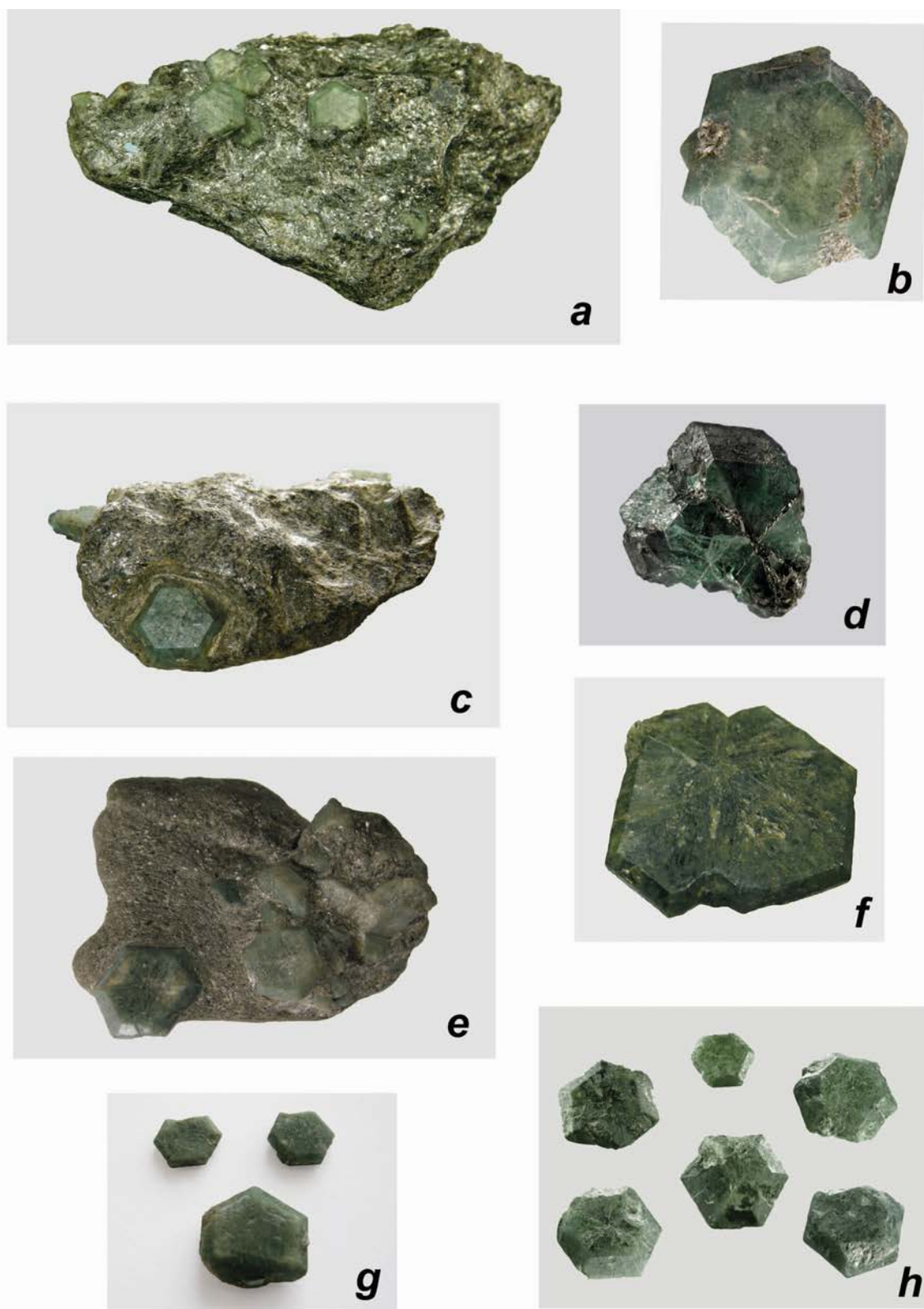
Fig. 5.10 a to h Cyclic twins (trillings) with tabular habit of alexandrite from the Tokovaya area, Urals, Russia; (b, d, f, g, and h) are cyclic twins, (a, c and e) show cyclic twins-on-matrix. Specimen locations and sizes are: a) Fersman Museum, 6 x 12 cm; b) Fersman Museum, 1.8 x 1.8 cm; c) Fersman Museum, 3.5 x 6 cm; d) private collection, 1.5 x 2.1 cm; e) Vernadsky Museum, 3 x 5 cm; f) Fersman Museum, 1.5 x 1.8 cm; g) private collection, sample below 1.2 x 1.2 cm; h) Museum für Naturkunde, the crystal on the lower right measures 1.5 x 1.5 cm. Photograph 5.10 d by P. Reith, all others by K. Schmetzer.
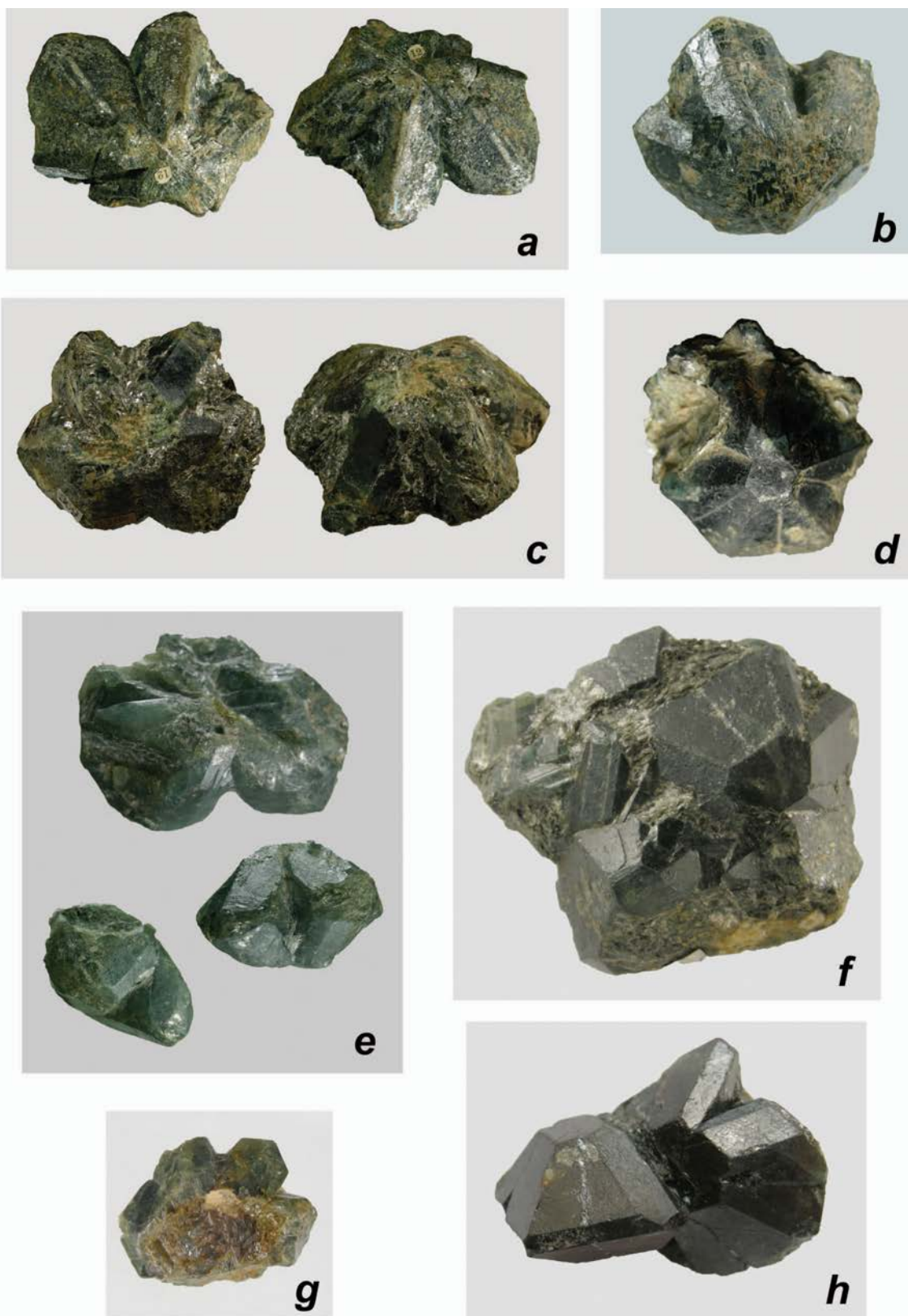
Fig. 5.11 a to h Cyclic twins (trillings) with dipyramidal habit (type 2) of alexandrite from the Tokovaya area, Urals, Russia; (a to e and g) are cyclic twins, (f and h) are crystal groups of cyclic twins. Specimen locations and sizes are: a) Fersman Museum, 5.5 x 7 cm; b) Natural History Museum, 2 x 3.5 cm; c) Fersman Museum, 6 x 7 cm; d) Fersman Museum, 3 x 3 cm; e) Museum für Naturkunde, different views, 2 x 3 cm; f) Saint Petersburg University, 3.5 x 4.5 cm; g) Natural History Museum, 1 x 1.5 cm; h) Saint Petersburg University, 1.5 x 2.5 cm. Photographs by K. Schmetzer.

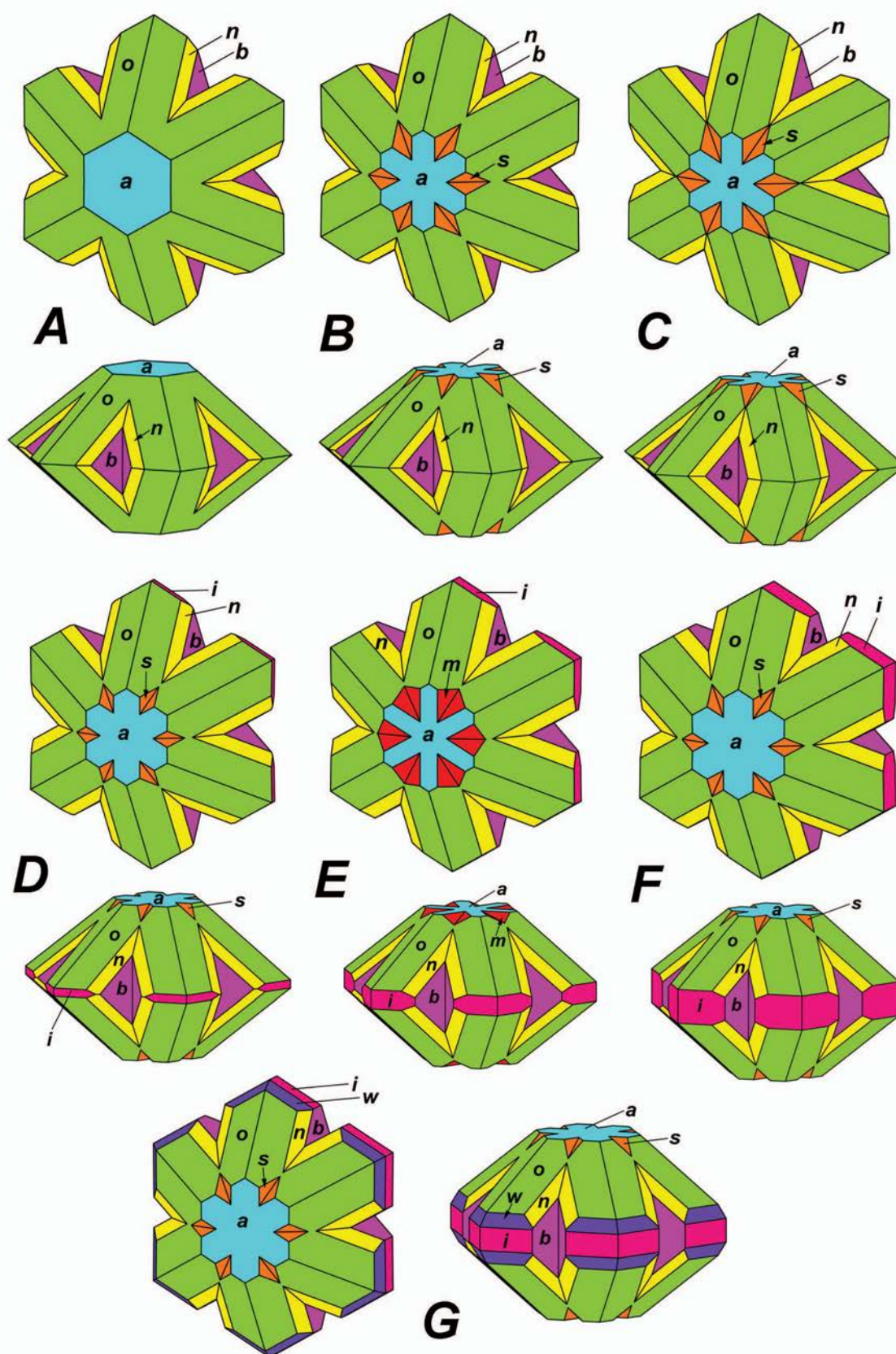**Fig. 5.12** Cyclic twins (trillings) with dipyramidal habit (type 2) (A to E) and dipyramidal habit (type 3) (F and G) of chrysoberyl and alexandrite from the Tokovaya area, Urals, Russia; (A to F) views parallel to the a-axis (upper rows) and perpendicular to the a-axis (lower rows); (G) view parallel to the a-axis (left) and perpendicular to the a-axis (right). Crystal drawings and artwork by K. Schmetzer.

In contrast, samples with dipyramidal habit, type 2, (**Fig. 5.11 a–h**) resulting from larger **o** faces and large re-entrant angles were common. Often museum specimens showed the spaces within these re-entrant angles are in-filled with mica. The re-entrant angles result from larger pinacoids **b**, from dipyramids **n** or from prism faces **s** (**Fig. 5.12 A, B**). Occasionally the re-entrant faces **n** and **s** are connected to each other and separate the dipyramids **o** of different individuals (**Fig. 5.12 C**). In rare cases, these cyclic twins also show small prism faces **i** (**Fig. 5.12 D**) as had already been illustrated by Koksharov. In a limited number of crystals, it was clearly shown that the re-entrant angles are also formed by the prism **m** (**Fig. 5.12 E**). Occasionally some distorted cyclic twins showed re-entrant angles for only part of the edges between **o** faces of the two individuals (**Fig. 5.13 a–c**).

In addition to these observations some further details not yet described in the literature were noted. These observations were made primarily on crystals collected after 1945, many of which originated from the Malysheva Mine. This was the most productive beryl-emerald-chrysoberyl-alexandrite mine in the years post 1945.

The first observation was done on cyclic twins with dipyramidal habit, type 3 (**Fig. 5.14 a–e**). In many samples of this type the prism **i** was larger (**Fig. 5.12 F**), and a further dipyramid **w** was observed (**Fig. 5.12 G**). Although it was mentioned once by Klein for a single crystal with a non-common habit, this form of cyclic twin was not described in the 19th century. Only one 19th century cyclic twin with that particular habit was noted from the collection of the Mining Institute in Saint Petersburg.
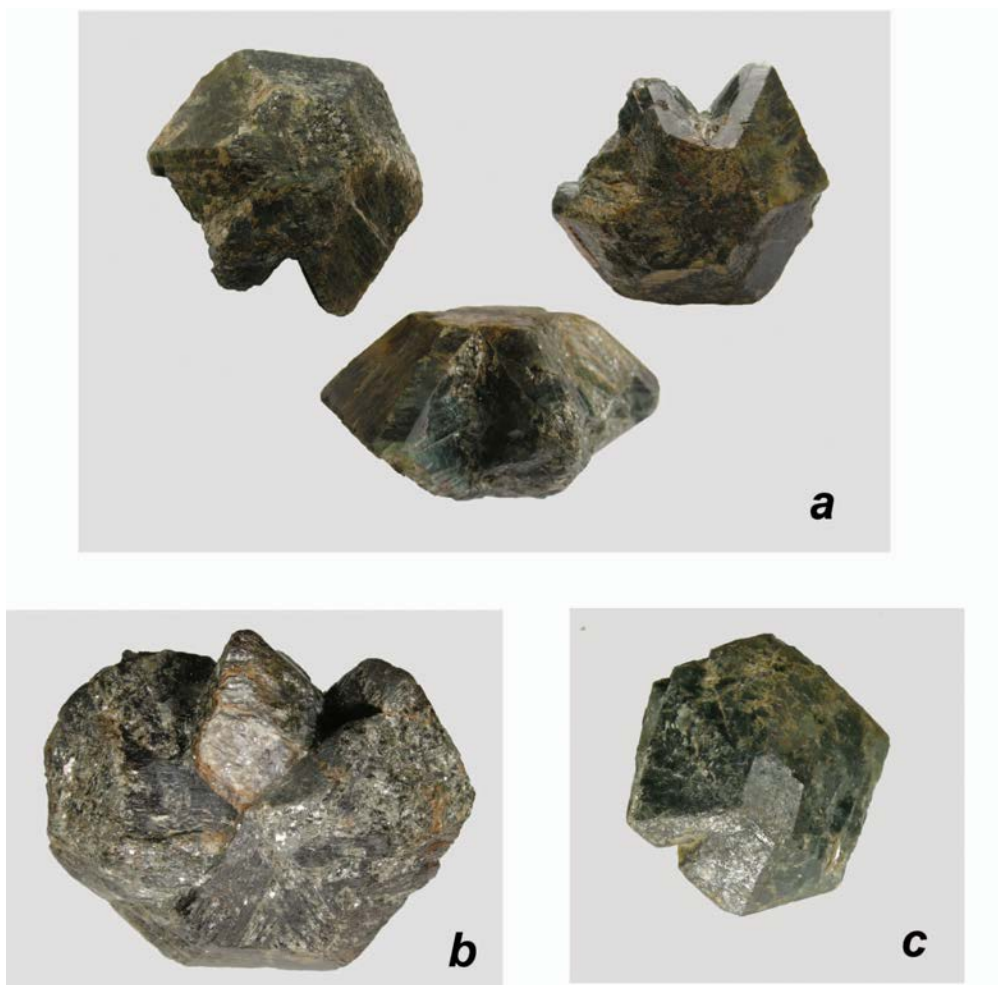
Fig. 5.13 a to c Distorted cyclic twins (trillings) with dipyramidal habit of alexandrite from the Tokovaya area, Urals, Russia. These crystals showed re-entrant angles for only part of the edges between **o** faces of different individuals. Specimen locations and sizes are: a) Saint Petersburg University, different views, 6.5 x 6.5 cm; b) Naturhistorisches Museum No. A. f. 394, 5 x 5 cm; c) Naturhistorisches Museum No. A.a.6128, 2.5 x 2.5 cm. Photographs by K. Schmetzer.
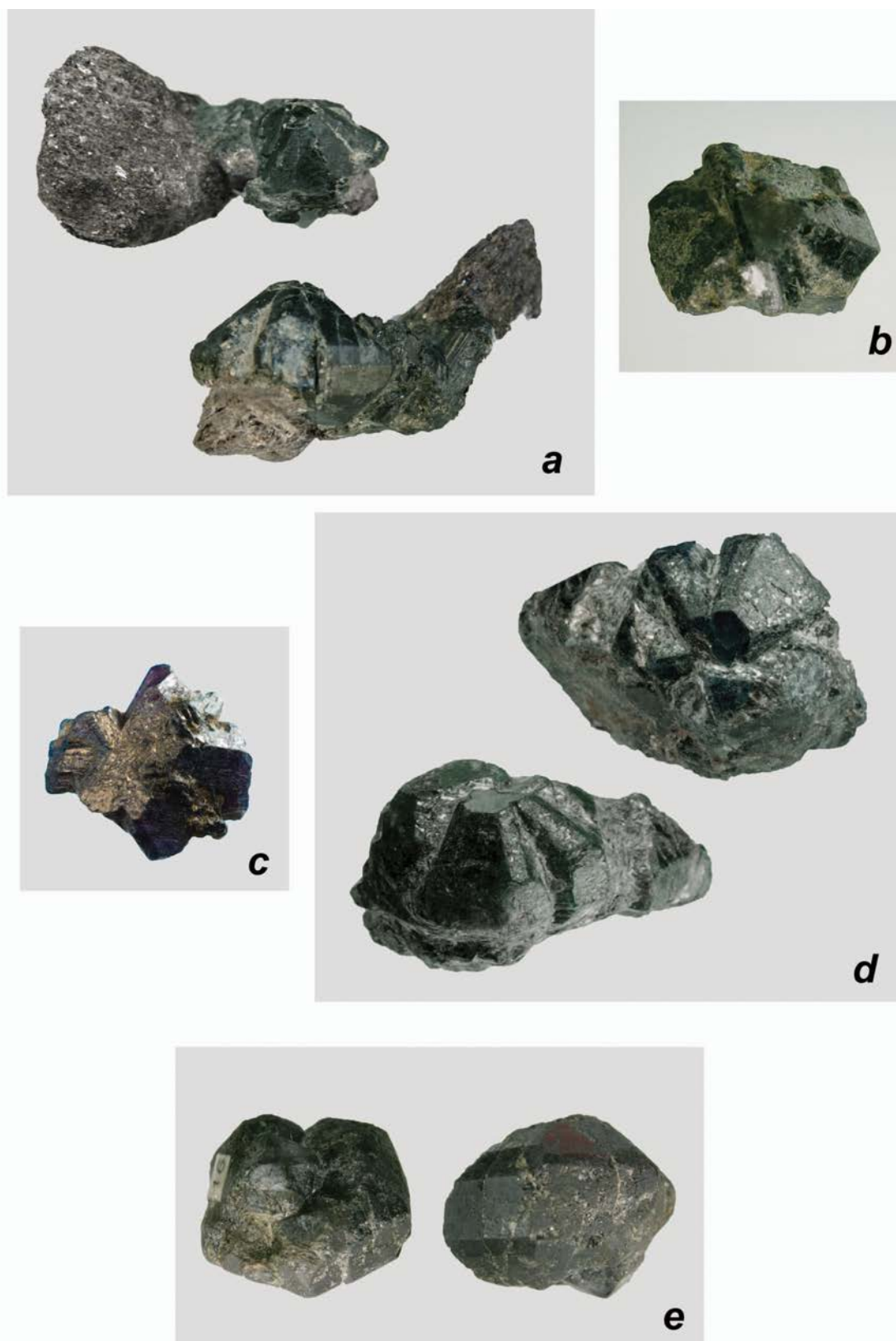
Fig. 5.14 a to e Cyclic twins (trillings) with dipyramidal habit (type 3) of alexandrite from the Tokovaya area, Urals, Russia; (b, c and e) are cyclic twins, (a and d) are cyclic twins with matrix. Specimen locations and sizes are: a) Schupp collection, different views, 2.5 x 4.5 cm; b) Schupp collection, 2 x 2.5 cm; c) Schupp collection, 1.2 x 1.4 cm; d) Schupp collection, different views, 1.5 x 2.5 cm; e) Vernadsky Museum, different views, 2 x 2.5 cm. Photograph 5.14 c by P. Reith, all others by K. Schmetzer.

Fig. 5.15 a to e Cyclic twins (trillings) with equidimensional to columnar habit of alexandrite from the Tokovaya area, Urals, Russia; (c and d) are cyclic twins, (a, b and e) are cyclic twins in matrix; (a to c) show samples in different views, (a, b and d) show samples in daylight and incandescent light, (c and e) show samples in incandescent light. Specimen locations and sizes are: a) Weise collection, different views, 2.5 x 4 cm; b) Weise collection, different views, 1.5 x 2.5 cm; c) Boyd collection, different views, 12 x 14 mm; d) Boyd collection, 10 x 11 mm; e) Boyd collection, 2.5 x 3 cm. The massive white material component of the matrix in samples (b) and (e) is plagioclase. Photographs 5.15 a and b by K. Schmetzer, 5.15 c and d by L. Kiefert, 5.15 e by P. Reith.

Furthermore, a habit change from dipyramidal to columnar was frequently seen (**Fig. 5.15 a–e, 5.16**). This change is the result of an increase in the relative sizes of the prism **i** and a decrease in size of the dipyramid **o**. As a result the habit of the pseudohexagonal cyclic twins changes from dipyramidal (**Fig. 5.17 A**) through equidimensional (**Fig. 5.17 B, C**) to columnar (**Fig. 5.17 D to F**). In columnar samples, only small or no dipyramid faces

o are present. Re-entrant angles caused by smaller pinacoids **b** were frequently present and restricted to mostly below 1 cm crystals. On several alexandrite crystal groups in matrix with equidimensional and columnar habit (**Fig. 5.16**), the ratio of sizes of different faces varies considerably. For example in one sample a crystal with the **o**: **i** ratio of 1: 1 is present together with another crystal with the **o**: **i** ratio of 1: 3.
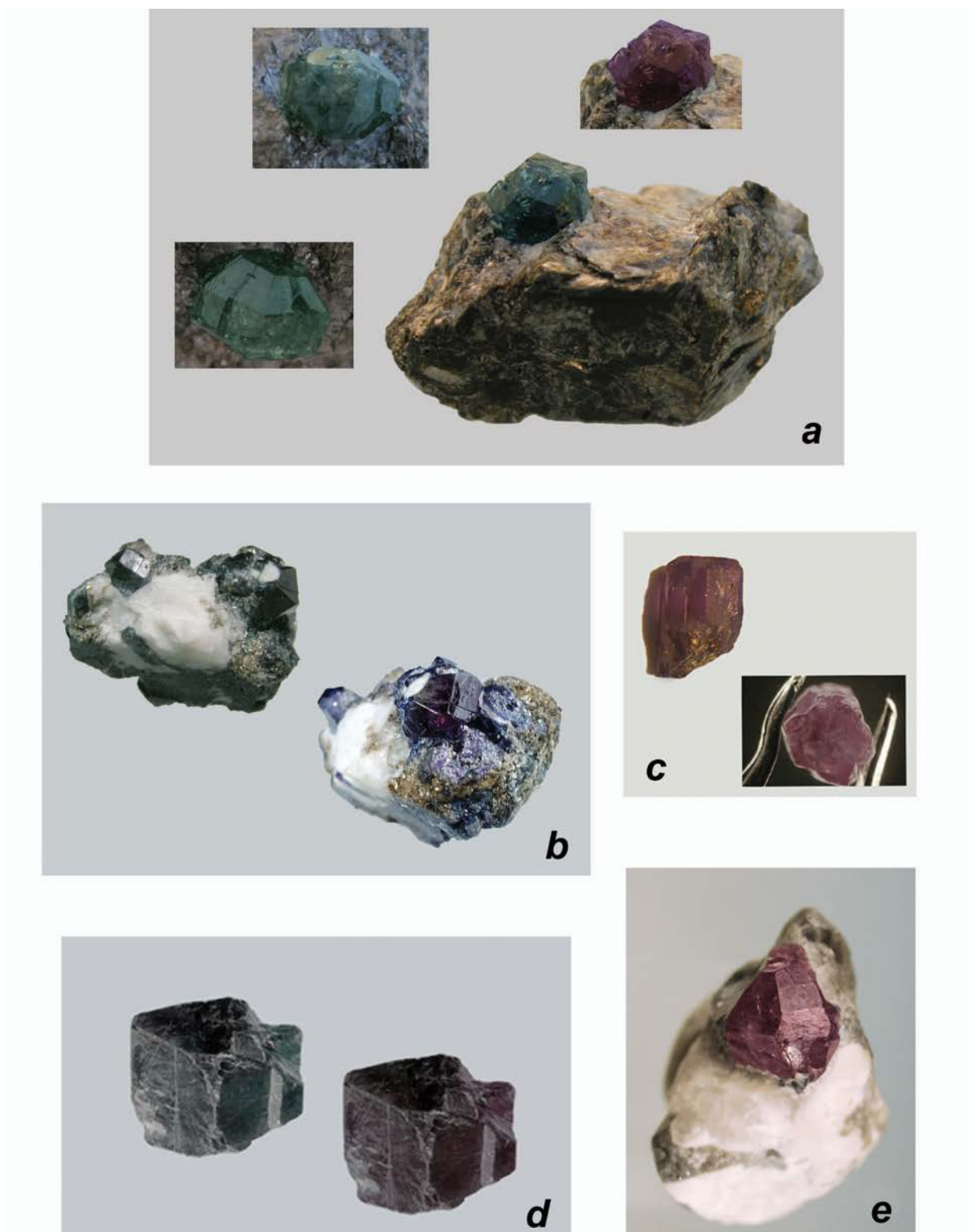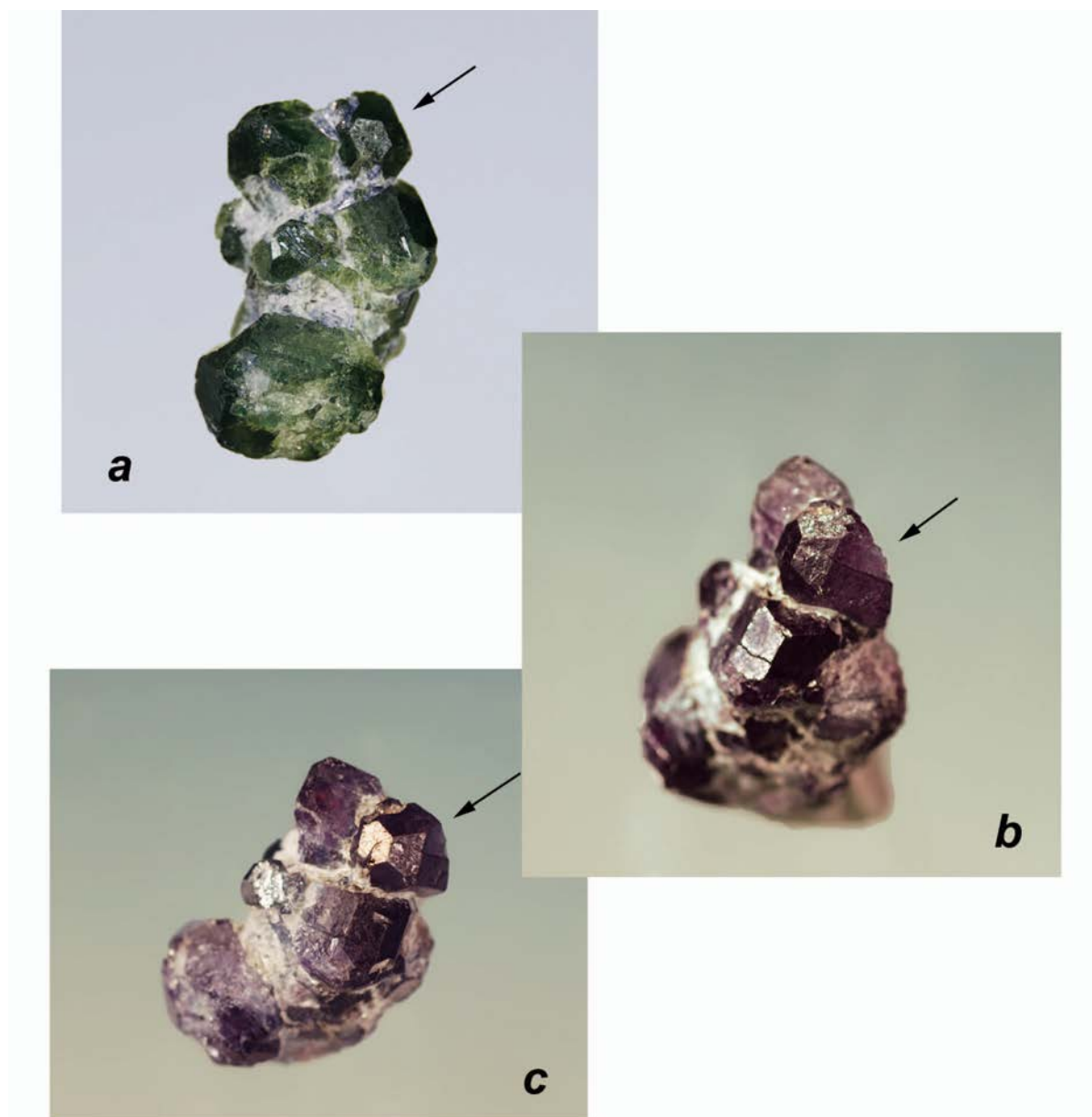

Fig. 5.16 Crystal group with cyclic twins (trillings) with equidimensional to columnar habit of alexandrite from Tokovaya area, Urals, Russia in daylight (a) and incandescent light (b,c); the photos were taken with different orientation of the sample and show one particular crystal (arrows) parallel (a), perpendicular (b) and oblique (c) to the a-axis. Boyd collection, 2 x 3 cm. Photographs by P. Reith.
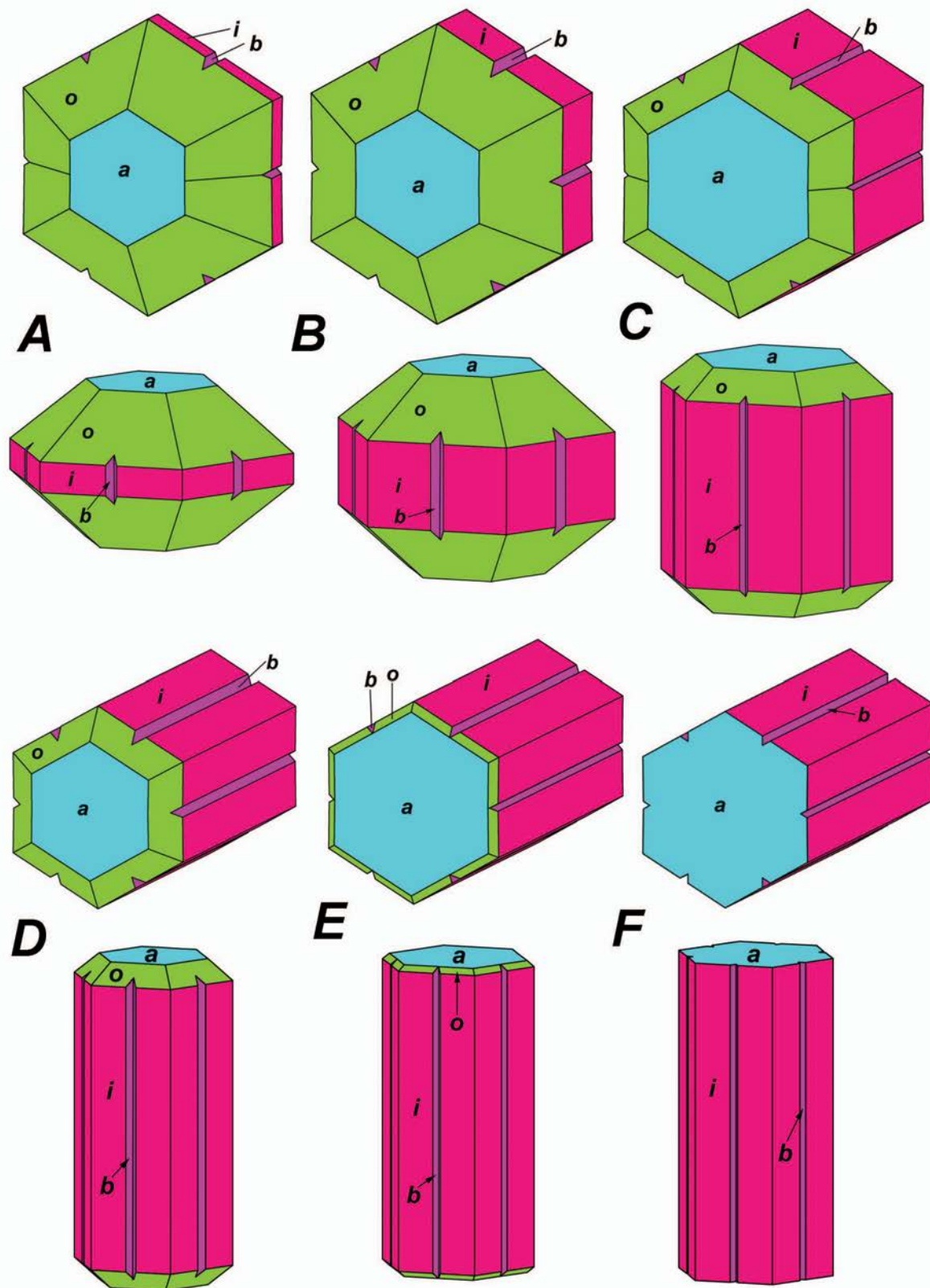
Fig. 5.17 Cyclic twins (trillings) of chrysoberyl and alexandrite from the Tokovaya area, Urals, Russia with dipyramidal (A), equidimensional (B and C) and columnar habits (D to F), views parallel to the a–axis (upper rows) and perpendicular to the a–axis (lower rows). Crystal drawings and artwork by K. Schmetzer.
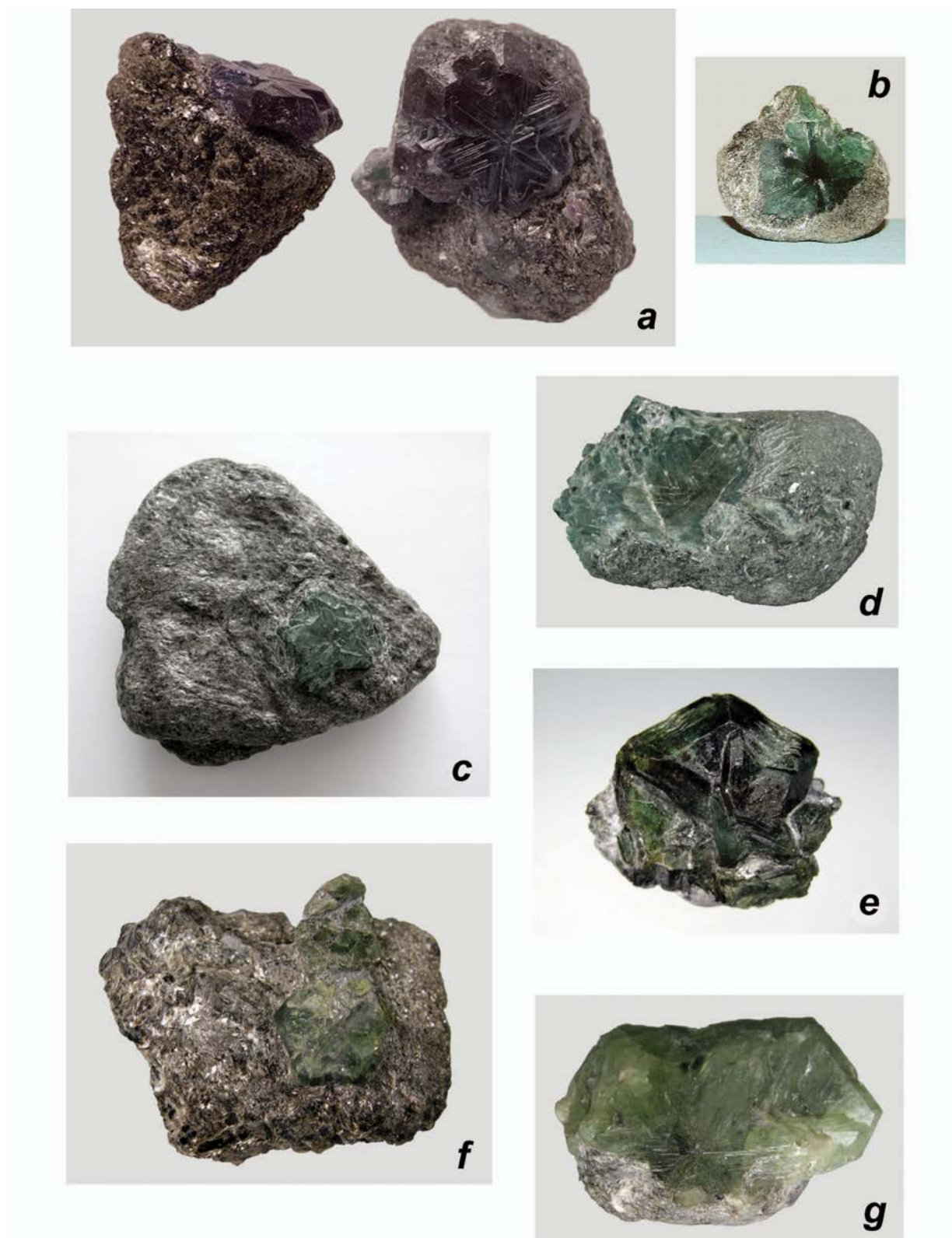
Fig. 5.18 a to g Cyclic twins (trillings) of alexandrite from the Tokovaya area, Urals, Russia, that show a mosaic-like surface structure due to the oscillating growth of different faces. Specimen locations and sizes are: a) Collection of Paul Wild Company, Idar-Oberstein, different views, incandescent light, 4 x 4 cm; b) Mineralogical Museum at the Urals State Mining University, Ekaterinburg, 4 x 4 cm; c) Schupp collection, 6.5 x 7 cm; d) Schupp collection, 4.5 x 7.5 cm; e) Weise collection, 2 x 2 cm; f) Vernadsky Museum, 3.5 x 5 cm; g) Vernadsky Museum, 3.5 x 5 cm. Photographs 5.17 a by the P. Wild Company; 5.17 b by G. Bosshart; all others by K. Schmetzer.
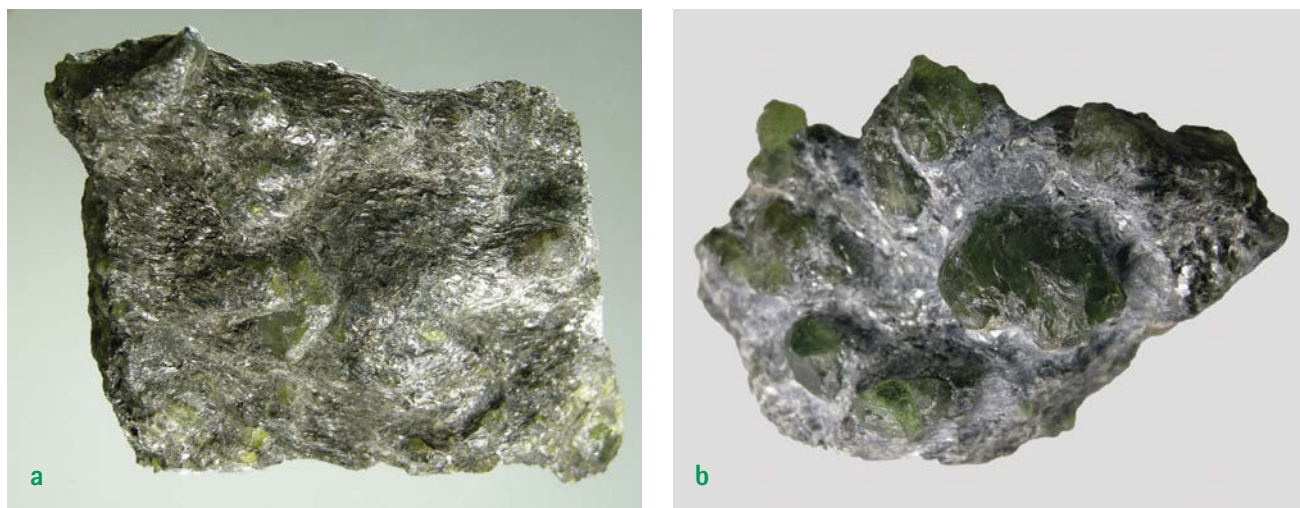
Fig. 5.19 a and b Small crystals of green chrysoberyl in a micaceous matrix. Specimen locations and sizes are: a) Museum für Naturkunde, 4.5 x 6.5 cm; b) Vernadsky Museum, 2 x 3.5 cm. Photographs by K. Schmetzer.

Numerous samples that were inspected showed a skeletal mosaic-like surface structure (**Fig. 5.18 a–g**). A detailed examination revealed that this structure was due to oscillating growth of different faces; mainly the pinacoid **a**, the prism **i,** the dipyramid **o**, and also possibly the pinacoid **b**. Obviously, these crystals formed under oscillating, frequently changing growth conditions.

Green chrysoberyl, without significant crystal morphology and mostly in micaceous matrix, was also frequently seen in various museum collections (**Fig. 5.19 a, b**).

(a) The largest alexandrite group ever found in Russia, **Kochubei's druse,** was discovered in 1840 in the Krasnoboltsky mining field within the southern part of the Tokovaya gemstone belt. The crystal group is described as consisting of 22 alexandrite trillings, the largest one measuring slightly over 7 cm diameter. The druse measures approximately 14 x 20 cm and weighs 5.38 kg. In 1862 it was part of the famous Kochubei collection. Drawing by W. Enderleit, lithograph by A. Munster, published by Koksharov (1862 a,b).

(b) Since 1913 the famous alexandrite sample described as **Kochubei's druse** has been housed in the Fersman Museum, named after A. Ye. Fersman. Photograph by K. Schmetzer.

(c) According to the 250th anniversary publicity in 1966, **Kochubei's druse** has been used as a symbol of the Fersman Museum. The museum was founded by Peter the Great in Saint Petersburg in 1716 as the Mineral Cabinet of the Kunstkammer and was later moved to Moscow in 1934. Photograph by K. Schmetzer.

6 Mineralogical and gemmological properties

Karl Schmetzer and Lore Kiefert [1]

6.1 Mineral assemblages

To determine whether the various crystal habits described in the previous chapter were the result of different mineral assemblages, small amounts of material were taken from the matrices of rough alexandrite crystals and examined using Raman microspectroscopy. Although sufficient small grains from rough crystals and crystal groups adhere to the hands of the examiner more material was removed, with permission of the owners, to allow examination of at least 3 to 5 tiny grains from each sample. Samples were selected to include all different habits as well as from all different time periods commencing with those from the Leuchtenberg collection in Munich, that came to the museum before 1850 and ending with samples obtained from the Malysheva Mine in the 21st century.

Raman spectroscopy was performed with a confocal Renishaw 1000 Raman system equipped with a 514 nm laser and operated with GRAMS32 software. Raman spectra were taken between 200 and 1800 cm^{-1}.

Altogether the main matrix minerals from 55 alexandrite crystals and crystal groups were examined. Phlogopite was determined as the main matrix mineral component in 53 samples representing all different habit types, different time periods and probably different locations within the Tokovaya mining area (**Fig. 6.1**). Two samples with equidimensional to columnar habit from the recent production of the Malysheva Mine contained margarite mica as the main matrix mineral. Two samples of the same habit contained massive white matrix components that were identified as plagioclase (**Fig. 6.1**). Fluorite occurred as an accessory component of the mica matrix in a few rock samples.

To further characterize the main component of the mineral assemblages, several tiny phlogopite crystals in 5 samples were examined by electron microprobe and 5 others by SEM-EDX analyses. All the examined phlogopite crystals were iron- and fluorine-bearing, and showed chemical variation in the iron and fluorine content of the samples.
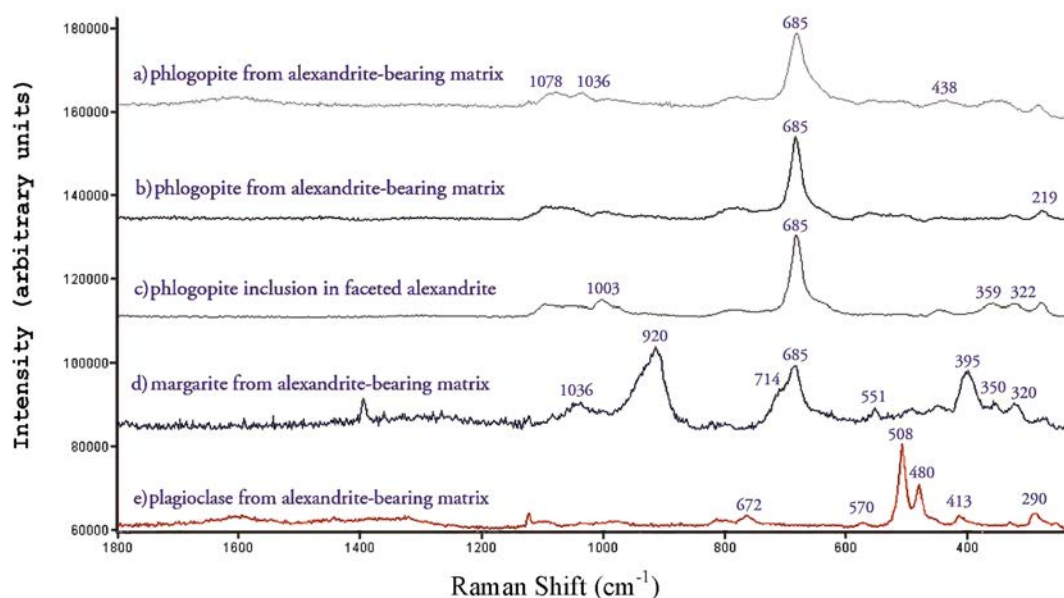

Fig. 6.1 Raman spectra of phlogopite inclusions in faceted alexandrite as well as spectra of phlogopite, margarite and plagioclase, the main mineral species within the matrices of alexandrite crystals and crystal groups.

These studies contradicted the first working hypothesis that suggested that different crystal habits might have been associated with different matrix mineral assemblages. However, it was shown that all different crystal habit types are associated with a predominantly phlogopite mica matrix and that some of the crystals with equidimensional to columnar forms have an association with margarite mica or with plagioclase.

In a few samples some additional lines within the Raman spectra of micas were observed that could not be assigned to the standard spectra of phlogopite. These lines were always found at more or less identical positions, the strongest lines at 815, 971, 1003, 1452, and 1728 cm^{-1}. Two phlogopite samples with these additional Raman peaks were examined by SEM-EDX and showed some chlorine in addition to the elements generally observed for phlogopite. These additional Raman lines, indicating chlorine, were attributed to the intentional or unintentional organic contamination of sample surfaces as recently described as a general problem with museum specimens[2].

6.2 Gemmological properties

The colour of faceted alexandrite in daylight varied from different intensities of green or bluish green. Intense green and intense to lighter bluish green samples changed to purplish red or reddish purple in incandescent light (**Fig. 6.2**); lighter green samples changed to violet or purplish violet. Samples that are very light green, yellowish green or yellow green in daylight did not show any remarkable colour change and are designated green, yellowish green or yellow green chrysoberyl rather than alexandrite.[3]

Alexandrite shows strong pleochroism. This was partly described by von Pott from a slice of a trilling cut perpendicular to the a-axis and for all three directions by Haidinger.[4] In the orientation used in this book the following scheme was observed[5] for polarized daylight and polarized incandescent light:

	DAYLIGHT	INCANDESCENT LIGHT
X ‖ a	violet purple to purple	reddish purple to purplish red
Y ‖ b	yellow green	yellow orange
Z ‖ c	blue green	blue green

The strongest hue change between daylight and incandescent light is observed for Y, a somewhat smaller change for X, whilst Z is almost unchanged.

The colour and pleochroism viewed parallel to the three crystallographic axes in non-polarized light is discussed in detail in chapter 9 and summarized in **Table 4**. The most prominent hue change to the unaided eye in non-polarized light is that parallel to the c-axis, whilst in views parallel to the a- and b-axes, hue changes

Fig. 6.2 This extraordinary 27.71 ct Russian alexandrite from the Rolf Goerlitz Company, Idar-Oberstein, Germany shows a distinct colour change from daylight (top row, left) to incandescent light (top row, right). The extent of colour change is demonstrated in the photograph below that shows the sample in incandescent light without any colour correction. Photographs by K. Schmetzer.

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[2]　Elder et al. (1997); Vandenabeele et al. (2000 a, b).
[3]　For a detailed study of colour and colour change see chapter 9.
[4]　von Pott (1842c); Haidinger (1847, 1849).
[5]　See also Schmetzer et al. (1980).

are distinctly smaller. The strongest pleochroism in daylight is between X and Y, viewed parallel to c, and in incandescent light between Y and Z, viewed parallel to a.

Refractive indices varied from 1.740 to 1.752 for n_x and from 1.748 to 1.760 for n_z with a birefringence Δn of 0.008 to 0.009. Specific gravity was determined in the range of 3.69 to 3.75.

6.3 Chemical properties

To characterize the alexandrite samples from the Urals qualitative chemical data of 35 faceted gemstones and 10 rough crystals without matrix were collected by energy-dispersive X-ray fluorescence (EDXRF) spectroscopy using an EDAX DX-95 X-ray fluorescence spectrometer.

The alexandrites examined show varying amounts of titanium, vanadium, chromium, iron and gallium (**Fig. 6.3**). It is out of the scope of this work to correlate the amount of the colour-causing trace elements, mainly chromium and iron, to the intensity of colour change (see chapter 9). The application of trace element contents for locality determination is addressed in detail in chapter 10.
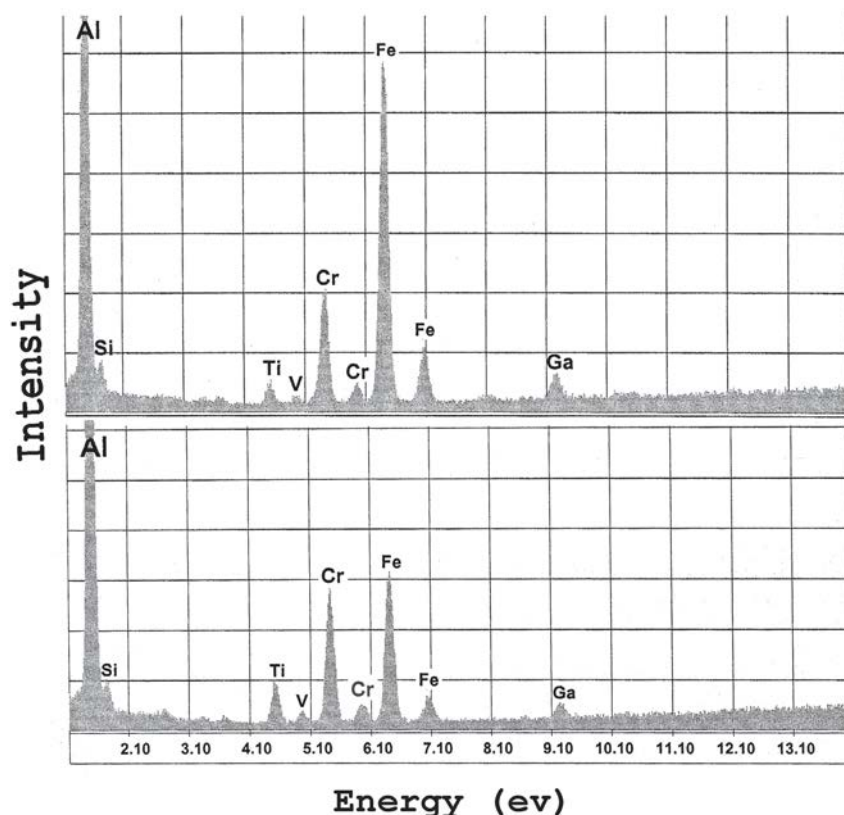
Fig. 6.3 Trace element contents in alexandrites from the Tokovaya area, Russia are variable as demonstrated by X-ray fluorescence spectroscopy. Distinct amounts of colour-causing trace elements, mainly V, Cr, and Fe, as well as variable amounts of Ti and Ga were observed in most samples; small peaks of silicon indicate the presence of silicate inclusions, mostly phlogopite mica.

6.4 Microscopic properties

Examination of faceted stones showed some to have numerous growth structures, several of which exhibited complicated growth patterns. However, it is not easy to determine the orientation of growth planes in relation to crystal axes. In optically biaxial chrysoberyl it is time consuming searching for the optic axes using interference patterns and then, using this information, determining the orientation of the crystal axes and evaluating the growth patterns by the stepwise application of this information. Because of this, focus is given to the dominant growth pattern frequently seen in faceted stones that consist of twinned individuals or single crystals.

6.4.1 Examination of structural properties (twinning and growth structures) in alexandrite

For the examination of structural properties it is necessary to observe a faceted alexandrite in different orientations by rotating it through 360° in the sample holder. The observed structural properties and their orientations within the gemstone relative to the table facet were noted. Orientation of alexandrite samples into special settings, followed by subsequent rotations, will give the information necessary to determine the most characteristic structural properties. Some examples that follow illustrate this procedure better than the theoretical considerations.

Example 1: Initial information from a microscope observation shows the sample has different growth planes and one twin boundary. The twin boundary is identified from its interference pattern (**Fig. 6.4 a**) or from the pleochroism observed in a view parallel to the twin boundary (**Fig. 6.4 b, c**). Upon rotation of the sample about an axis perpendicular to the twin plane, the twin boundary remains sharp under the microscope. A series of growth planes perpendicular to the twin plane (**Fig. 6.4 d**) is observed in one particular orientation; these may be the prism **i**, pinacoid **a** or dipyramid **o**. Then the twin boundary is inclined by rotating about an axis perpendicular to the growth planes which remain sharp under the microscope. With this step, another series of growth planes are observed forming an angle of 140° with the first series (**Fig. 6.4 e**). In alexandrite this measured angle is formed between adjacent dipyramidal faces **o** (**Table 2**). Consequently the pattern observed comprises a series of **o** growth planes in the first individual of the twin, designated **o1**, and parallel **o** growth planes within a second individual of the twin, designated **o2**. Furthermore, the pattern consists of dipyramidal **o** planes adjacent to the **o1** planes of the first individual, designated **o1'**.

Example 2: In a situation similar to example 1, under the initial microscope observation the sample shows different growth planes and one twin boundary. In one particular orientation, the sample shows a series of growth planes perpendicular to the twin boundary (**Fig. 6.4 f**). In the same orientation these growth planes in each part of the twin intersect an additional set of growth planes forming two characteristic angles of 120°. This indicates that all growth planes are prism faces **i**, with parallel prism faces **i1** and **i2** in both parts of the twin together with adjacent prism faces **i1'** and **i2'**.

Example 3: This sample shows various growth planes and three twin boundaries (**Fig. 6.4 g, h**). With rotation of the polarizer, the pleochroism within the three parts of this trilling can be observed. This indicates that the alexandrite is cut in such a way that it reveals all three cyclic twin planes with the intersecting edges parallel to the crystallographic a-axis. In a view parallel to this axis, the growth planes seen are parallel to the prisms **i** and upon further rotation, other characteristic growth planes can be determined.

Examples 1 to 3 above describe twinned individuals. By keeping the orientation of an observed twin boundary in the faceted alexandrite in mind, it is possible to orientate the sample in such a way under the microscope, as to allow a view perpendicular to a twin plane. In this orientation, the most typical growth pattern of chrysoberyl and alexandrite can be seen. This pattern is also seen in untwinned single crystals when orientated the same way under the microscope as described in example 4 below.

Example 4: The faceted alexandrite shows no twin boundary but several sets of growth planes associated with distinct pleochroism and strong colour zoning. In one particular orientation a pattern consisting of three sets of growth planes can be observed (**Fig. 6.4 i, j**). The two dominant sets in the centre intersect at an angle of 86°, and each of these forms an angle of 133° with another series of growth planes. This observation is consistent with a pattern formed by two opposite dipyramids **o1** and **o1'** of the alexandrite and one prism **i** at its centre. When rotating the alexandrite about a perpendicular axis to the pinacoid **a**, this characteristic pattern is sometimes repeated. In another orientation of the same crystal, a growth pattern consisting of two series of planes forming an angle of 72° can be observed (**Fig. 6.4 k,l**). This pattern is assigned to two diagonal dipyramids **o1** and **o1'**.

6.4.2 Twinning

Although most natural alexandrites from the Uralian deposits are cyclic twins or trillings, many of the faceted stones are untwinned. This can be understood by considering the probabilities of cutting twinned and untwinned stones from larger rough trillings that are heavily fractured and included. If an alexandrite was cut from the outer parts of crystals with larger re-entrant angles, the faceted sample will not show any twinning. If the faceted stones were cut from crystals without re-entrant angles or from the centre of samples with larger
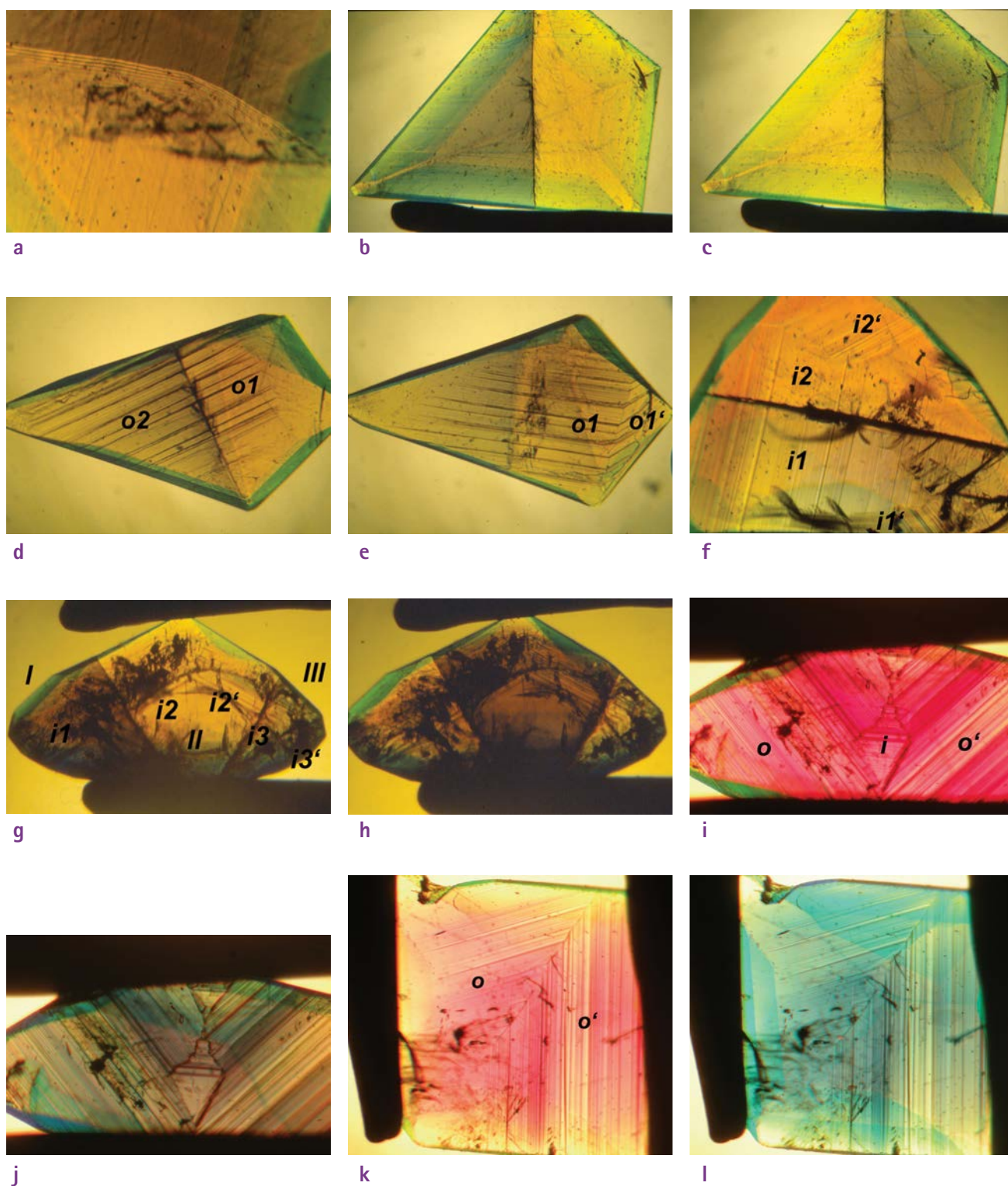
Fig. 6.4 a to l Examples of typical microscopic features in alexandrites from the Tokovaya area, Urals, Russia showing: (a) twin boundary with interference pattern; 50x, I, # pol.; (b and c) twin boundary showing pleochroism by rotation of the polarizer; 40x, I; (d) view parallel to the twin plane, showing the growth pattern parallel to the **o** dipyramid; 40x, I; (e) growth pattern consisting of two <u>adjacent</u> **o** dipyramids; 40x, I; (f) view parallel to the twin plane, growth pattern shown parallel to adjacent **i** prisms; 40x, I; (g and h) trilling with two twin boundaries showing pleochroism upon rotation of the polarizer; 40x, I; (i and j) growth structures with pleochroism upon rotation of the polarizer showing two <u>opposite</u> **o** dipyramids and one **i** prism; 40x, I; (k and l) same sample as (i and j) after rotation showing two <u>diagonal</u> **o** dipyramids; 50x, I. All photographs by K. Schmetzer; I = immersion, # pol. = crossed polarizers.
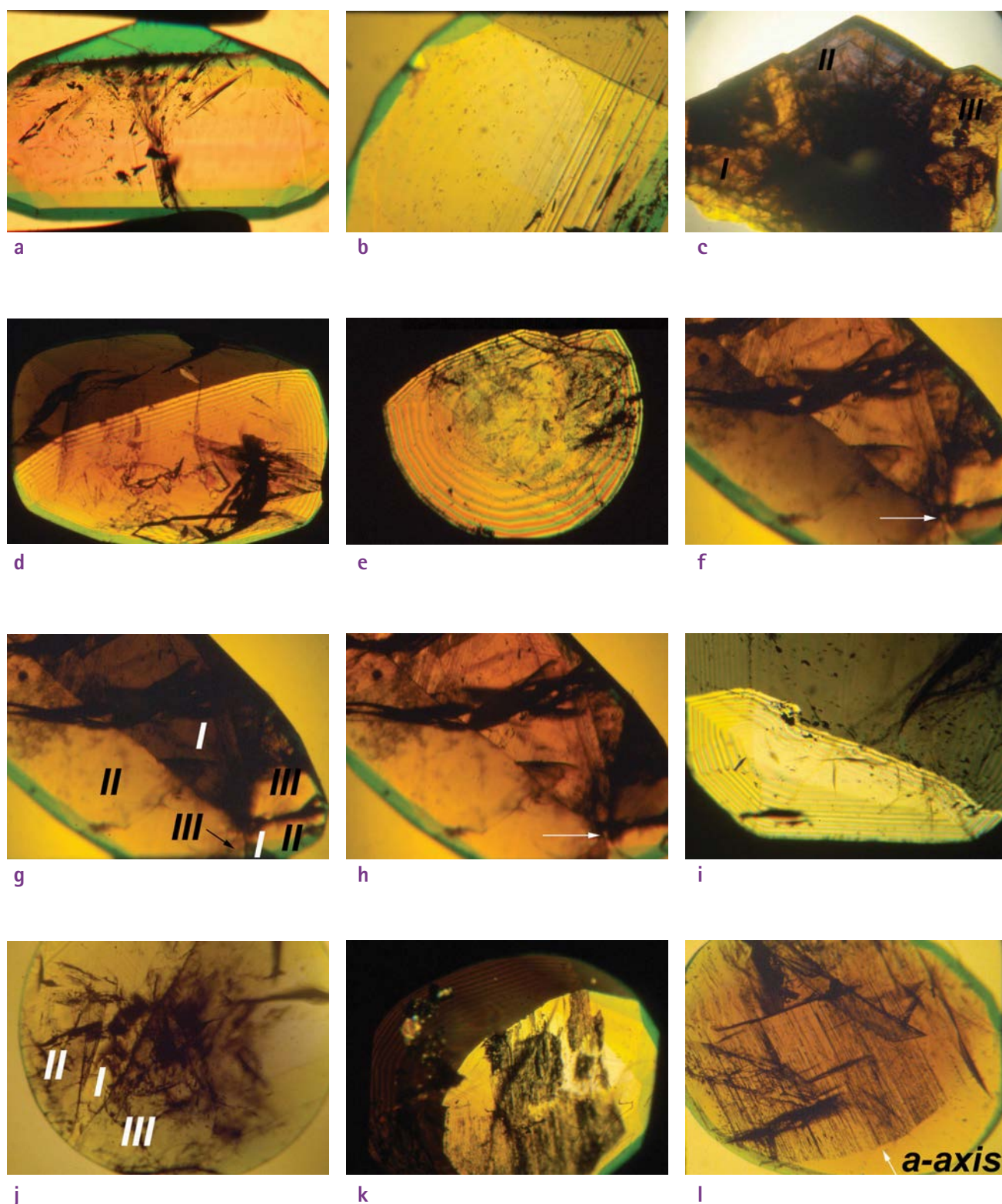
Fig. 6.5 a to l Twinning and structures related to twinning in alexandrites from the Tokovaya area, Urals, Russia: (a and b) twin boundaries and pleochroism; 40x, I; (c) trilling with two twin boundaries and pleochroism; 15x, I; (d and e) twin boundary with interference pattern; 30x, I, # pol.; (f, g and h) trilling with two twin boundaries showing pleochroism upon rotation of the polarizer; 25x, I; (i) irregular twin boundary with interference pattern; 50x, I, # pol.; (j) irregular twinning; 30x, I, # pol.; (k) irregular twin boundary with interference pattern; 30x, I, # pol.; (l) twin boundary with needle-like structures parallel to the a-axis; 40x, I. All photographs by K. Schmetzer; I = immersion, # pol. = crossed polarizers.

re-entrant angles or from smaller trillings, it is more likely that they would show twinning. Only when a faceted stone is cut from the centre of a trilling, would all three individuals of that trilling be present.

These theoretical considerations that are based on the morphology of rough specimens can be confirmed by microscope observations. Of the examined faceted Russian alexandrites, some were untwinned crystals, some were twins and only a few showed more than one twin plane or the complete centre section of a crystal with all three trilling individuals. Under polarized light different individuals of the twin or the trilling can easily be observed. This is because of the combination of the distinct pleochroism of chromium-bearing chrysoberyl and the different orientations of the individuals of twins (**Fig. 6.5 a, b**) and trillings (**Fig. 6.5 c**). Interference colours related to the twin boundary are observed under crossed polarizers (**Fig. 6.5 d and e**).

One faceted sample, containing the complete centre of the crystal, consisted of one dominant individual with the other individuals as contact twins on both sides (**Fig. 6.5 f, g and h**). This dominant crystal showed a growth pattern similar to an hourglass structure.

In most cases twin boundaries are planar structures, but occasionally show steps or other irregular structural elements (**Fig. 6.5 i**). Irregular twinning formed by irregularly intergrown individuals was rarely observed (**Fig. 6.5 j**). Usually twin boundaries are transparent contact planes, but can frequently be decorated with inclusions (**Fig. 6.5 k**). Occasionally, twin boundaries contain numerous parallel lines or needle-like structures that are always orientated parallel to the a-axis [100] and perpendicular to the pinacoid **a** (**Fig. 6.5 l**). This orientation can be proven if two intersecting twin boundaries are present. From structural considerations the intersection edge between such twin planes in chrysoberyl is always parallel to the a-axis.

6.4.3 Growth structures

The most characteristic growth pattern seen in Russian alexandrites can be observed in a view perpendicular to a twin boundary. This pattern can also be observed in untwinned single crystals. A general overview is given in **Fig. 6.6**. The pattern is formed by combinations of the dominant faces: the prism **i**, the pinacoid **a** or the dipyramid **o** (**Fig. 6.7 a–i**). In addition growth planes parallel to the dipyramid **w** can also be seen in this orientation.
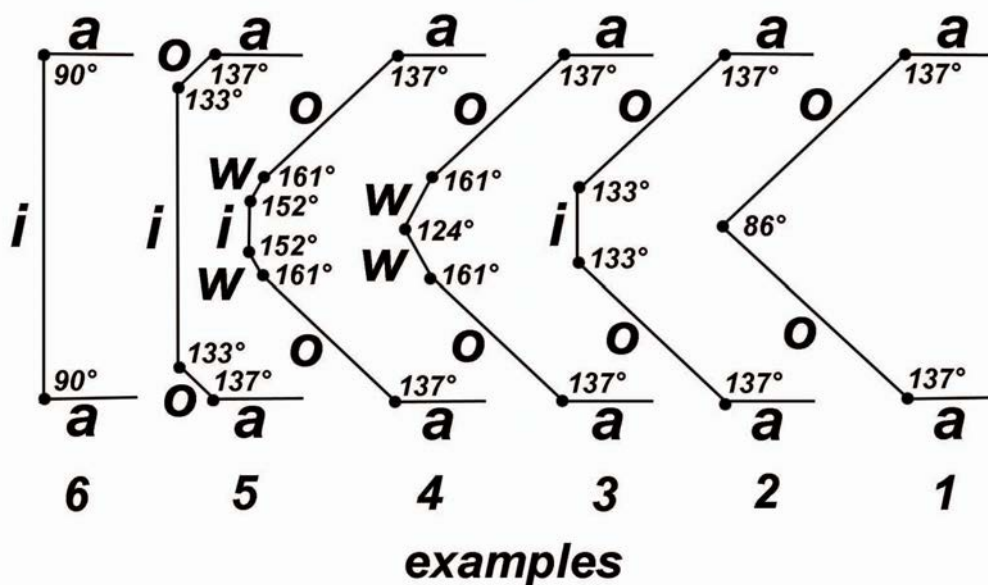
Fig 6.6 Examples of the most characteristic growth patterns in Russian alexandrites are observed in a view perpendicular to a twin boundary. In untwinned samples, the pattern is also observable in the same direction of view. The patterns consist of various combinations of the **a** pinacoid, the **i** prism and two **o** and **w** dipyramids. Characteristic interfacial angles formed by these faces are also given. A combination of some of the given examples, 1 to 6, reflects the habit change of part of the alexandrites during crystal growth. Artwork by K. Schmetzer.

A growth pattern consisting of the faces **aoww'o'a'** or **aowiw'o'a',** or part of these sequences, is the most usual type observed in Uralian alexandrites, especially those from the Malysheva Mine obtained after 1945. The same pattern without the dipyramids **w,** comprising a combination of **aoo'a'** or **aoio'a',** or part of these sequences, was frequently observed. Occasionally, part of these growth patterns were seen combined with colour zoning parallel to these different faces.

If the a-axis of an alexandrite twin or single crystal is orientated parallel to the rotation axis of the immersion microscope, the typical growth pattern described above can be seen repeatedly. If, based on the information available, the dominant dipyramids **o** within the growth pattern are identified, it would be possible to observe and identify a pattern consisting of adjacent **o** and **o'** faces (**Fig. 6.7 j**) or a pattern consisting of adjacent dipyramids **o** in combination with dipyramids **n** (**Fig. 6.7 k**). Occasionally, a pattern consisting of diagonal dipyramids **o** can also be seen (**Fig. 6.7 l**).

Colour zoning can be observed from both within the same growth sector and between different growth sectors (**Fig. 6.7 a–l**).

Occasionally, there can be a variation of the growth sequence from the centre to the rim of a crystal:

a) Only **oo'** growth faces appear in the centre with large faces **i** developed at the rim (**Fig. 6.8 a**, **Fig. 6.6 examples 1 and 2**).

b) Only **oo'** growth faces appear in the centre with **ww'** increasing towards the rim; between the centre and the rim, small faces **i** may develop but disappear again in later stages of growth (**Fig. 6.8 b–e, Fig. 6.6 examples 1 and 3 or 1, 2, 3**).

c) The centre shows a characteristic **oww'o'** sequence, and towards the rim faces **i** increase in size (**Fig. 6.8 f– k, Fig. 6.6 examples 3 and 4**).

d) The centre shows **aowiw'o'a'**, and **w** and **o** subsequently decrease leaving only **a** and **i** at the end of crystal growth (**Fig. 6.8 l, Figure 6.6 examples 4, 5, 6**).

Crystal drawings **Fig. 5.9** and **5.12 A–F** show specimens with only **oo'** and no growth sequence or samples with sequence a) as above; **Fig. 5.12 G** with sequences b) and c) and **Fig. 5.17** with the sequence d).

6.4.4　Mineral and fluid inclusions in faceted stones

Chrysoberyl, not alexandrite, from the Urals was analysed previously using Raman spectroscopy.[6] The authors described muscovite and plagioclase (oligoclase) together with two-phase and three-phase fluid inclusions. Various plagioclases from the emerald mines, characterized by X-ray diffraction and chemical analyses, showed a compositional range from albite to andesine.[7]

Although rough alexandrite is often found embedded in a matrix composed mostly of fine grained phlogopite mica, samples containing mineral inclusions of sufficient size for identification by Raman microspectroscopy were rare. In the current research project some 15 faceted samples, representing about 10 % of the examined gemstones, were selected to determine their solid mineral inclusions. The instrument used is described in section 6.1.

The majority of mineral inclusions were determined by Raman spectroscopy as phlogopite (**Fig. 6.1**). The phlogopite flakes and more irregular crystals appear colourless under the microscope (**Fig. 6.9 a–h**). Fluorite and apatite crystals were identified in a few samples.

The numerous internal fractures in the alexandrite crystals are filled with liquid and two-phase inclusions that contain a liquid and gas or occasionally liquid and birefringent mica (**Fig. 6.9 i–l**). The Raman analyses of a few larger cavities revealed the presence of CO_2.

6　Gromalova et al. (2006).
7　Meiksina and Evdokimov (2003).
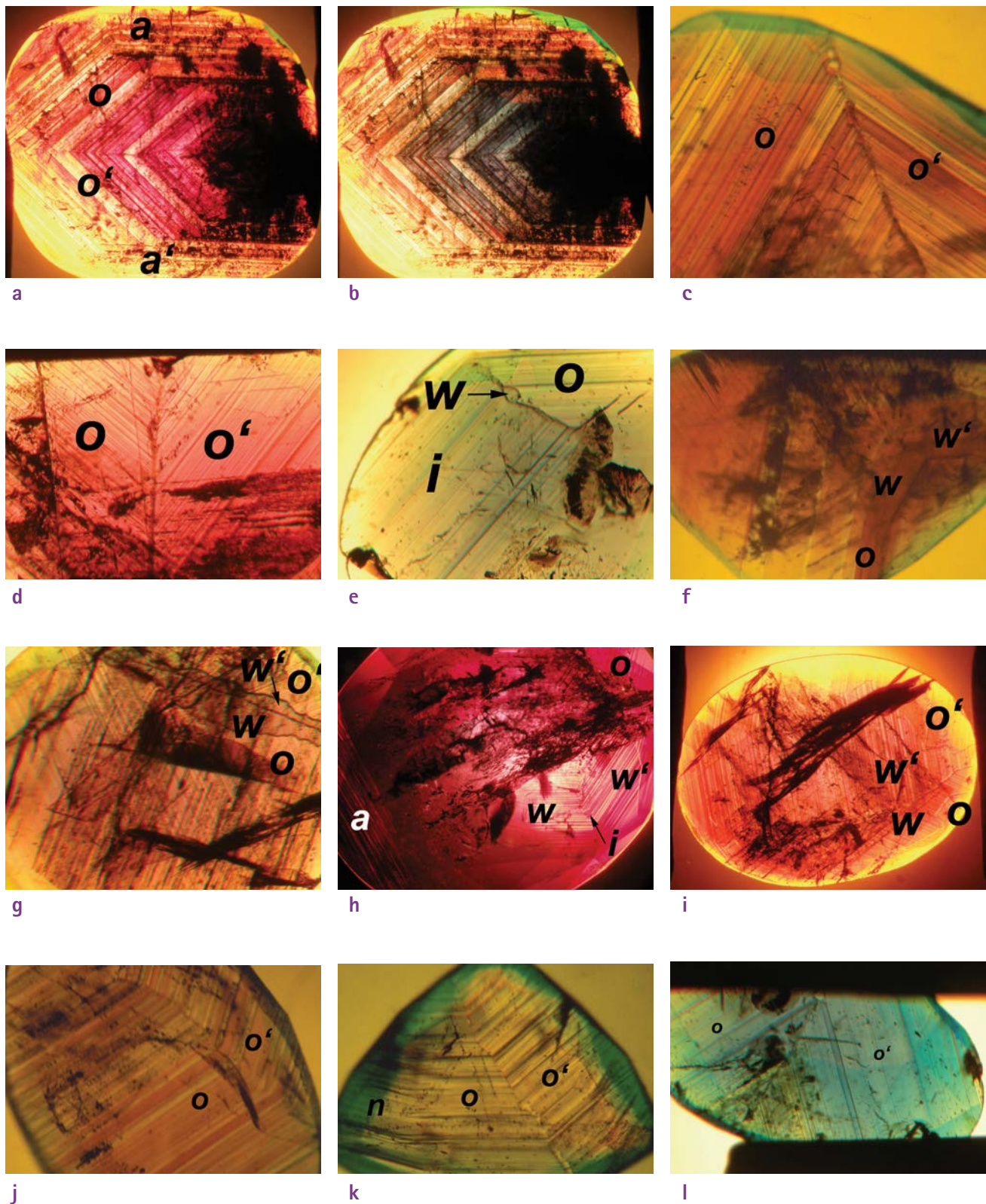
Fig. 6.7 a to l Growth structures in alexandrites from the Tokovaya area, Urals, Russia, are frequently associated with colour zoning; characteristic angles are formed by combinations of the dominant faces forming the morphological pattern and habit of the sample (see Figure 5.1). (a to i) show opposite **o** dipyramids, forming angles of 86°; (j and k) show adjacent **o** dipyramids, forming angles of 140°; (l) shows diagonal **o** dipyramids, forming an angle of 72°. All photographs by K. Schmetzer; I = immersion, # pol. = crossed polarizers; (a, b, h and i): 30x, I; (c, d, e, g and l): 40x, I; (f, j, and k): 50x, I.
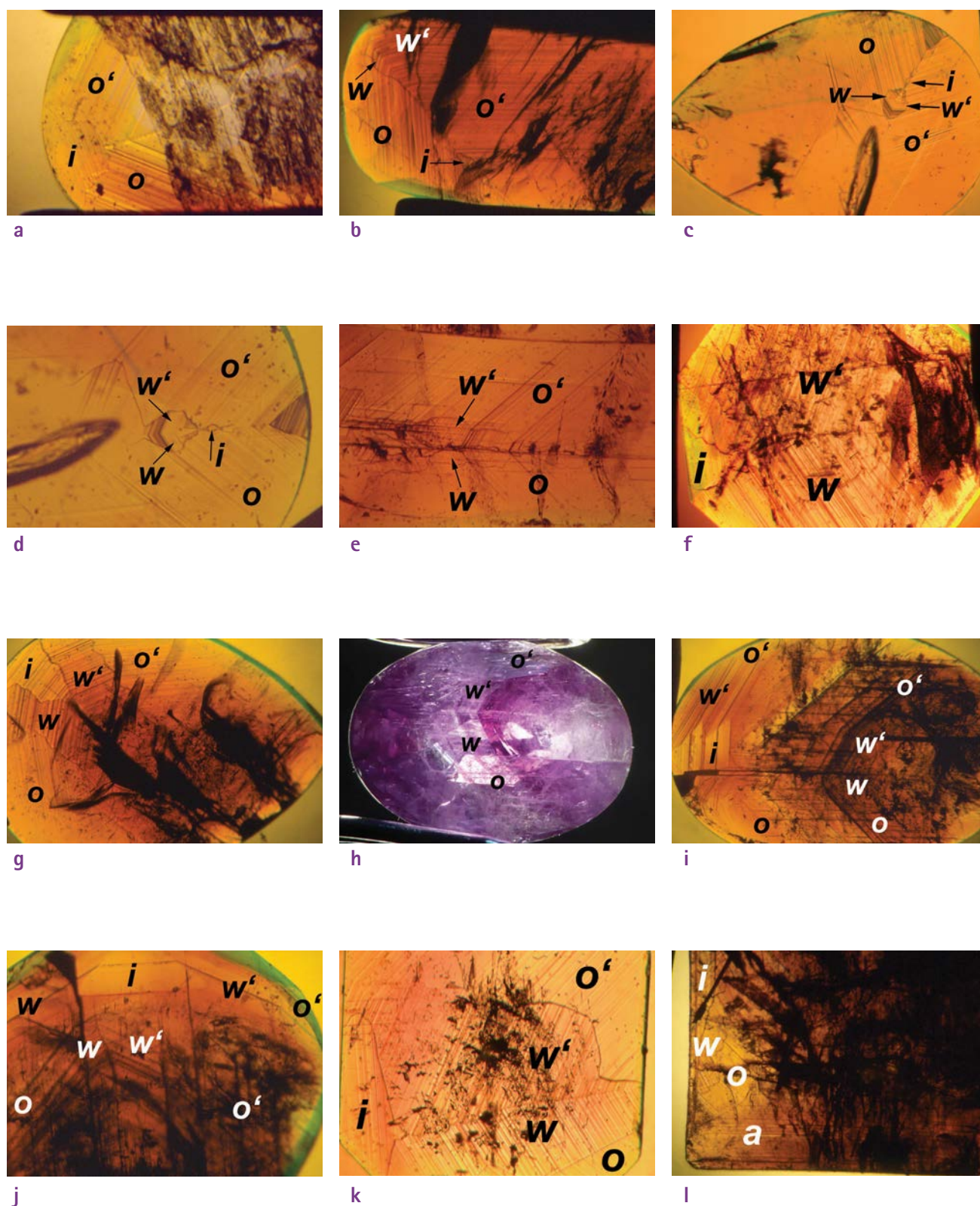
Fig. 6.8 a to l Growth structures in alexandrites from the Tokovaya area, Urals, Russia, frequently show a distinct habit variation from the centre to the rim of the crystal. (a) growth patterns with **o o'** in the centre and **o i o'** towards the rim; (b to e) growth patterns with **o o'** in the centre and **o w w' o'** towards the rim; (f to k) growth patterns with **o w w' o'** in the centre and **o w i w' o'** towards the rim; (l) growth patterns **a o w i** in the crystal and only **a** and **i** as external faces representing the last stage of crystal growth. Photograph 6.8 h by L. Kiefert, all others by K. Schmetzer; I = immersion, # pol. = crossed polarizers; (a, d, e and k): 50x, I; (b, c and h): 25x, I; (f): 40x, I; (i, j and l): 30x, I.
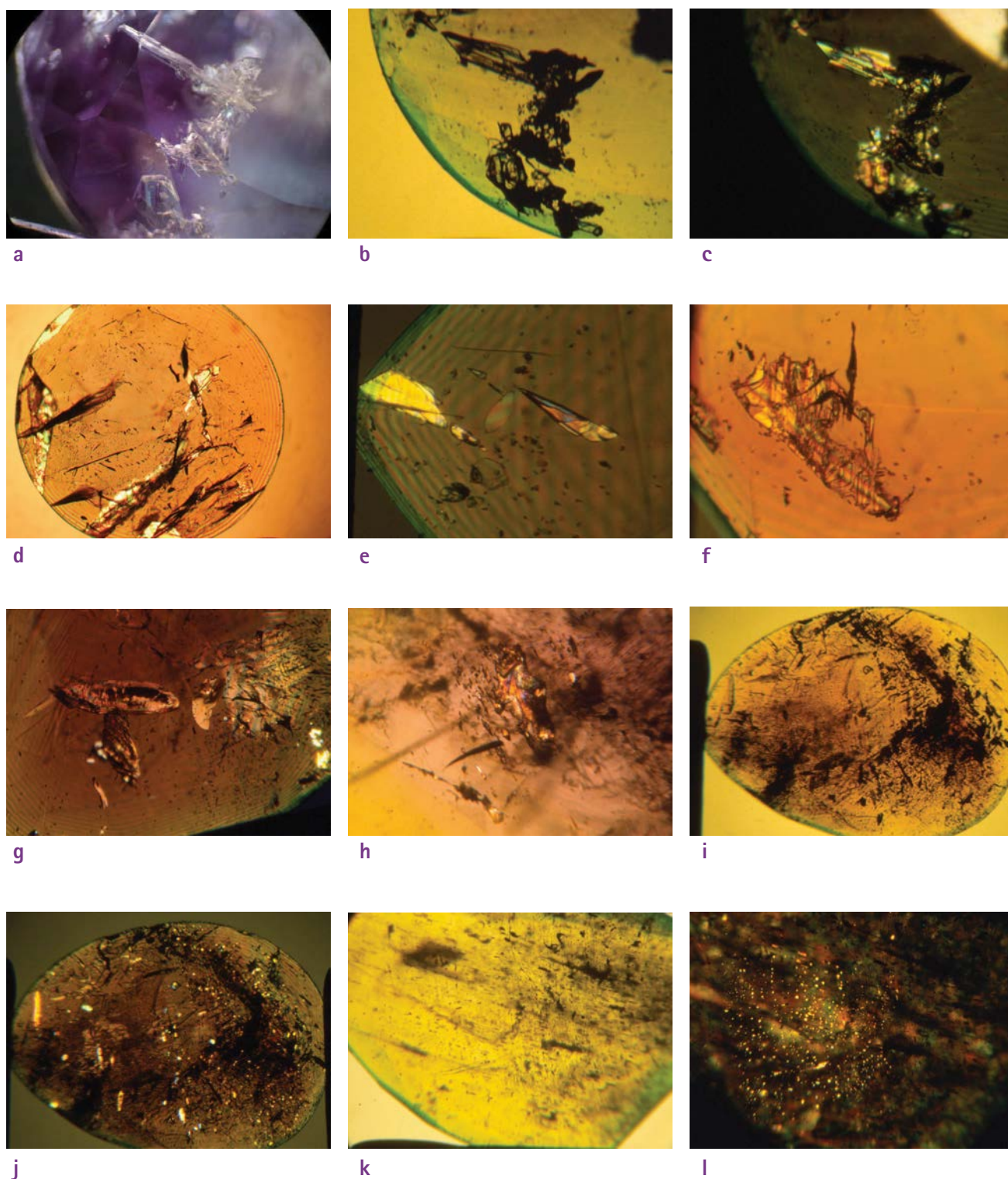
Fig. 6.9 a to l Many faceted Russian alexandrites are heavily fractured with healed or partly healed feathers consisting of liquid and two-phase inclusions. The most common mineral inclusion is phlogopite mica as flakes or platelets. Occasionally, tiny mica crystals were also seen as part of two- and three-phase inclusions. These are most readily seen under crossed polarizers: (a, b and c) same sample with mica flakes in reflected light (a), transmitted light (b and c) and under crossed polarizers (c); (d to h) samples with mica flakes shown under crossed polarizers; (i and k) two-phase inclusions; tiny mica flakes become visible under crossed polarizers (j and l). Photograph 6.9 a by L. Kiefert, all others by K. Schmetzer; I = immersion, # pol. = crossed polarizers; (a): 60x; (b): 60x, I; (c, e, and h): 60x, I, # pol.; (d): 30x, I, # pol.; (f and l): 70x, I, # pol.; (g and j): 40x, I, # pol.; (i): 40x, I; (k): 70x, I.

6.5 Mineral assemblages, growth conditions and growth sequences

Numerous Russian papers are available discussing the formation of beryl- and emerald-bearing ore bodies (frequently called glimmerites in Russian literature) in the Uralian emerald mines.[8] However, it is only recently that some research findings concerning the formation of chrysoberyl and alexandrite have been published. In older papers, it was mentioned that alexandrites were not found in close proximity to emeralds. Because of this, miners disliked finding alexandrite-bearing ore bodies or veins, as it indicated there would not be gem quality emeralds in these pits.

Various papers published from the early 1990s discuss the occurrence and formation of chrysoberyl and alexandrite in the Uralian emerald mining area in more detail. These papers are mainly based on observations of mineral assemblages and investigations of samples from the Malysheva Mine. Generally all authors[9] agree that the main occurrences of alexandrite are within emerald-bearing ore bodies, also known as glimmerites. Several authors also describe the occurrence of chrysoberyl and/or alexandrite in quartz-plagioclase veins[10] or in plagioclase-margarite-talc veins.[11]

It was possible to deduce two stages of alexandrite crystallisation within the main emerald-bearing glimmerite ore bodies. In the first stage chrysoberyl and emerald were formed within mica schist or a plagioclase-rich host rock. In the later second stage beryl (emerald), plagioclase, and chrysoberyl (alexandrite) crystallized. It is emphasised that mineral formation in the main ore body of the Malysheva Mine has to be regarded as a sequential process.[12]

Both historical specimens from museums and some of the more recent samples, mostly from the Malysheva Mine, show alexandrite with dipyramidal (type 1 and 2) and tabular habits in association with phlogopite mica. Most alexandrite samples from the Malysheva Mine are also associated with phlogopite and have a dipyramidal habit (type 3). Samples from the Malysheva Mine with equidimensional to columnar habits were found in association with phlogopite, phlogopite and plagioclase, or with margarite mica.

The interpretation of internal growth features was limited by a lack of pre-1900 material with a known history for microscope examination. Only a limited number of gem quality samples of recent origin from the Malysheva Mine was obtained before faceting. Most rough crystals were heavily included and fractured and this did not allow for the determination of growth sequences under the immersion microscope. Depending on the fraction of the original sample removed by the cutting process, some faceted samples only reveal part of the information of the complete crystal growth history. To achieve this would require the preparation of orientated thin sections and slices.

All faceted alexandrites examined showed growth features consistent with the external morphology described in chapter 5 (**Table 2**). Only some of the samples showed changes in morphology with a distinct habit change in crystal growth from the centre to the rim. The pinacoid **a** is not involved in this habit change, allowing the study to be concentrated on the other larger faces, namely **o**, **i**, and **w**. In some samples, a habit change from **o o'** in the centre to **o i o'** at the rim (represented by a sequence 1 → 2 of **Fig. 6.6**) was observed. Most commonly, there was an increase of **w** in addition to **o** and, in a later stage, the additional appearance of **i**. This stage of crystal growth is consistent with samples with dipyramidal habit of type 3 (represented by the sequence 1 → 3 → 4 of **Fig. 6.6**). In some samples with equidimensional to columnar habits there is a decrease in size of **o** or of **o** and **w** in favour of **i** and, in a last stage of crystal growth, only the presence of **i** in addition to **a** (represented by the sequence 4 → 5 → 6 in **Fig. 6.6**). In several samples there was clear evidence of oscillating growth. Certain faces such as **i** or **w**, showed firstly an increase in size and subsequently a decrease in size during later stages of crystal growth (represented by the sequences 1 → 2 → 1 or 1 → 3 → 1 in **Fig. 6.6**).

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[8] See, e.g., Kupriyanova (2002).
[9] Zolotukhin and Laskovenkov (1991); Ustinov and Chizhik (1994); Emlin (1996); Burlakov et al. (1997); Meiksina and Evdokimov (2005).
[10] Zolotukhin and Laskovenkov (1991).
[11] Emlin (1996); Burlakov et al. (1997).
[12] Ustinov and Chizhik (1994).

Probably, growth conditions for most historic samples unearthed from surface mining were slightly different from those obtained from the Malysheva Mine after 1945: the former showing a sharp edge between two opposite **o** faces or only small prism faces **i**. Conversely, the more recent Malysheva samples obtained by underground mining down to a present depth of 360 m below surface always showed strong prism faces **i,** frequently associated with dipyramids **w**, and with no sharp edges between opposite dipyramids **o**. A second morphological type of alexandrite from the Malysheva Mine comprises crystals with equidimensional to columnar habits. This habit type of alexandrite was neither previously described nor currently observed within "historical" samples and is possibly associated with the second, later, growth type of alexandrite within the complex formation of the main emerald- and alexandrite-bearing ore body at the Malysheva Mine.

Alexandrite crystal group shown in both daylight and incandescent light; this extraordinary piece was submitted to the Gemmological Laboratory, Liechtenstein for examination in 2009. The sample measures about 6.5 x 9 cm. Photograph by Th. Hainschwang.

7 Alexandrite cat's-eyes and chrysoberyl stars

Karl Schmetzer

Chatoyancy can be observed in chrysoberyl and alexandrite from numerous different sources. However, asterism in chrysoberyl is extremely rare and to the knowledge of the author, four-rayed asteriated alexandrite is only mentioned in one short description in the gemmological literature.[1]

Gemmological literature contains few notes on different types of star chrysoberyl. These include:

▶ Four-rayed star chrysoberyl with 90° light band intersections is mentioned by a few authors.[2]

▶ An asymmetrical six-rayed star chrysoberyl was described by G.I.A. Research service.[3]

▶ Four- and six-rayed star chrysoberyls from Sri Lanka with light bands inclined to each other are mentioned by Kumaratilake.[4]

In theory, the first example requires two series of 90°-orientated needle- or channel-like inclusions, and the second type of asterism requires two or three sets of inclusions inclined to one another.

The production of synthetic chrysoberyl and alexandrite cat's-eyes is described in numerous patent applications, many published in the 1980s,[5] and involves a two-step growth process. The first step involves the production of homogenous single crystals containing a specific dopant such as titanium. Such specifically-doped crystals can be grown by any known technique suitable for the crystal growth of chrysoberyl. The second step involves annealing at elevated temperatures in an oxidizing atmosphere. During this process elongated particles, most probably rutile needles, are precipitated and are responsible for the chatoyant effects of the material when cut as a cabochon.

7.1 Alexandrite cat's-eyes from Russia

Although it was possible to cut some Uralian samples as cabochons exhibiting chatoyancy, there is little appreciation for this type of gemstone in Russia and it is rarely done.[6] Although some samples were available (**Fig. 7.1 a**) microscope examination of these did not reveal individual needle-like inclusions, only darker, somewhat brownish areas.

It was possible to determine the orientation of the light band relative to the twin boundary and other growth structures in three twinned Russian alexandrite cat's-eyes (**Fig. 7.1 b**). From examination of these, it was deduced that the tiny needles responsible for the light band of the cat's-eye are oriented parallel to the a-axis and the light band itself is seen perpendicular to this direction and to

the needle axes of the tiny inclusions. This observation is consistent with the structural properties, as only the a-axes are parallel in twinned individuals. If it was otherwise, twinned alexandrite or chrysoberyl could display asterism more frequently, but this phenomenon is extremely rare in this mineral.

Only one Uralian alexandrite sample showed numerous needle- or channel-like inclusions that were inclined to the twin boundary of the crystal (**Fig. 7.1 c**). These were oriented parallel to the different c-axes of the twinned crystals that form an angle of 60° and paralleled the striations that are frequently seen on the pinacoid **a** of twinned and untwinned chrysoberyl and alexandrite (**Fig. 7.2**).

[1] Crowningshield (1963).
[2] Crowningshield (1960), Liddicoat (1976); Fryer (1989); Koivula and Kammerling (1989).
[3] G. I. A. Research Service (1937).
[4] Kumaratilake (1997).
[5] Shindo et al. (1982); Kunugi (1984); Oguri and Hirota (1985); Isogami and Nakata (1986); to mention only a few examples.
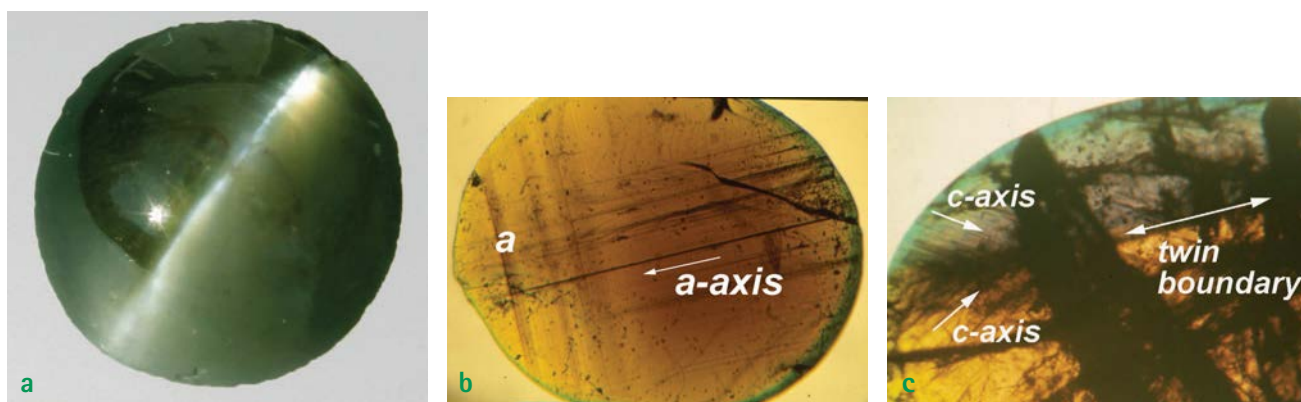[6] Personal communication from V. Repei (2008).

Fig. 7.1 a to c (a) 3.30 ct alexandrite cat's-eye from the Tokovaya area, Urals, Russia. Schupp collection. (b) Alexandrite cat's-eye from the Tokovaya area, Urals, Russia; view perpendicular to a twin plane, small needle-like inclusions are present in a direction perpendicular to the **a** pinacoid; 50x. (c) Alexandrite from the Tokovaya area, Urals, Russia. Numerous needle- or channel-like inclusions are inclined to the twin boundary and run parallel to the c-axis, parallel to the striations that are frequently seen on the **a** pinacoid of both twinned and untwinned chrysoberyl and alexandrite; 20x, all photographs by K. Schmetzer.
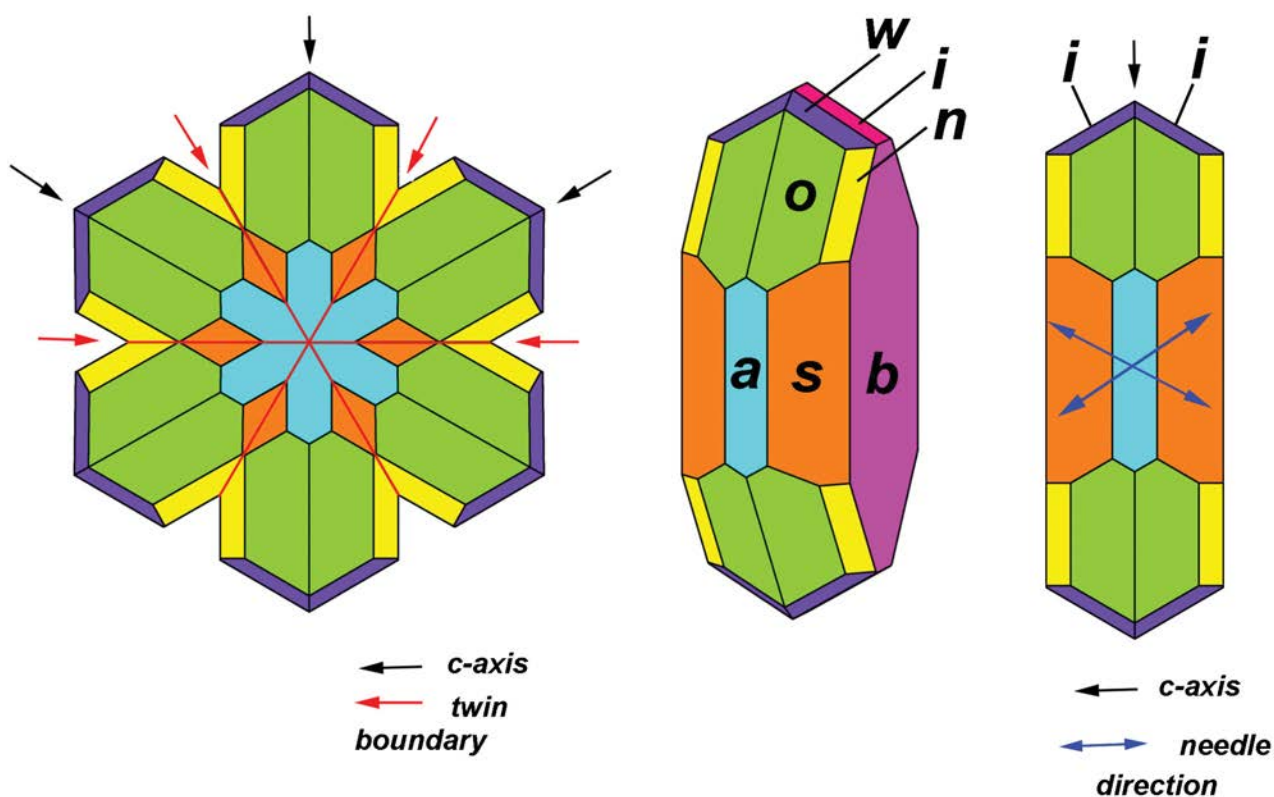

Fig. 7.2 Diagrams showing the orientation of channels and needles in chrysoberyl and alexandrite. Left: view parallel to the a-axes showing how channels and needles parallel to the c-axes form angles of about 60° with each other and angles of about 30° with the twin boundaries in cyclic twins. Centre: Clinographic view of an untwinned chrysoberyl crystal. Right: the same crystal rotated and viewed parallel to the a-axis showing the orientation of channels and needles parallel to two **i** prisms forming angles of about 60 and 120° with each other. Crystal drawings and artwork by K. Schmetzer.

7.2 Alexandrites from Sri Lanka with needle-like inclusions

In the course of this study a comparison was made between some alexandrite from Sri Lanka and material from Russia. Three faceted samples from Sri Lanka showed areas with a dense concentration of inclusions. Microscopic examination was difficult in these areas of the stones, but three individual sets of needles were noted from the zone between transparent parts without needle-like inclusions and the dense translucent areas (**Fig. 7.3 a**). Additionally, these samples were twinned and were easily oriented under the microscope (**Fig. 7.3 b**). The following observations confirm the conclusions made earlier from Russian samples and illustrate the possible causes of asterism in chrysoberyl.

1) The alexandrites have a predominant set of needles that are parallel to the a-axis [100] in both single crystal and twinned examples.

2) The alexandrites show two additional sets of needles, both of which are inclined at 90° to the first set and additionally inclined to each other at approximately 120° (**Fig. 7.2, Fig. 7.3 b**). These two sets of needles were oriented parallel to the prism **i** in the directions [011] and [01$\bar{1}$].

These observations assist in the understanding of asterism in chrysoberyl. Assuming that different sets of needles in similar concentration are present and that the sample is cut as a cabochon in a direction in which the light bands caused by different sets of needles are visible, the following observations would be made:

a) If one set of needles is oriented parallel to the a-axis, these needles produce a light band in the b-c plane.

b) If one set of needles is oriented parallel to [011] or [01$\bar{1}$], these needles produce a light band in a plane intermediate between the a-b and the a-c planes.

c) If one set of needles parallel to the a-axis, the usual direction of needles in chrysoberyl or alexandrite cat's-eyes, and one set of needles parallel to [011] or [01$\bar{1}$] are present, a 90° four-rayed star would be formed.
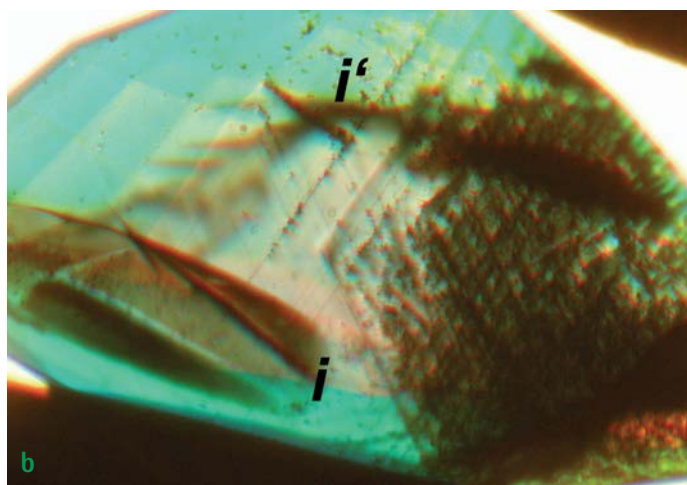
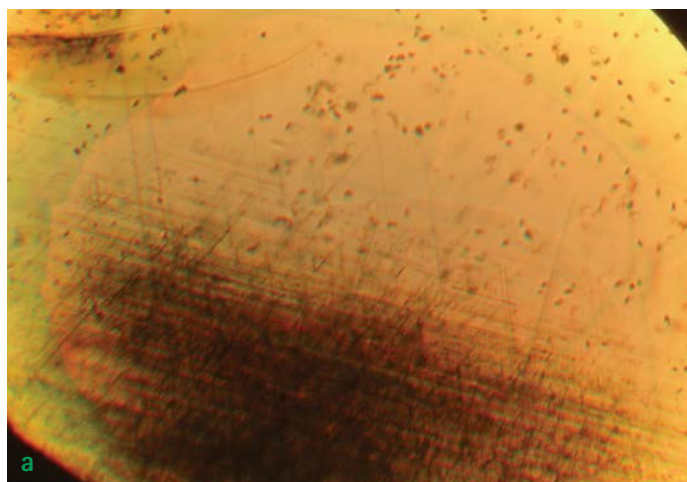**Fig. 7.3 a and b** (a) Three series of needle-like inclusions are seen in a faceted alexandrite from Sri Lanka. 60x. (b) Three series of needle-like inclusions are seen in a faceted alexandrite from Sri Lanka. View parallel to the a-axis. Needles of the first series run parallel to the a-axis, needles of the second and third series run parallel to two **i** prisms. 50x. Photographs by K. Schmetzer.

7.3 Asteriated chrysoberyl from Sri Lanka

This general explanation of the rare asterism of chrysoberyl required further experimental work to show that the considerations presented above are confirmed with star chrysoberyls. For the present study, four asteriated samples, probably originating from Sri Lanka, were available. Three samples showed a 90° four-rayed star more or less in the centre of the samples (**Fig. 7.4 a**) and one sample showed four-rayed asterism with somewhat inclined arms of the star (**Fig. 7.4 b**). However, examining this sample in an orientation with the light source exactly parallel to the direction of view confirmed that the arms of this sample also intersected at right angles. The identity of all four asteriated cabochons was confirmed as chrysoberyl by Raman spectroscopy.

The samples examined were untwinned chrysoberyls. In part of the samples, one set of needles was observed, with individual needles that were distinctly smaller than those described in section 7.2 for alexandrites from Sri Lanka. Several other sets of needles, when present, were not resolved using the normal magnification of gemmological microscopes.

For one sample showing a 90° four-rayed star consisting of two somewhat stronger arms and two somewhat weaker arms (**Fig. 7.4 a**) it was possible to observe both optical axes in the immersion microscope after appropriate orientation of the sample. With this observation the optic plane, also called optical axial plane (OAP), the a-c plane in chrysoberyl, was known and it was possible to determine the approximate position of all three rhombic axes a, b, and c of the chrysoberyl cabochon (**Fig. 7.5 a, b**). The light bands forming the four-rayed star were located in the b-c plane and between the a-b and a-c planes. These observations indicate that the four-rayed star is caused by two sets of needles: parallel to the a-axis and parallel to [0kl], most probably parallel to [011].

Using a second sample showing four-rayed asterism (**Fig. 7.4 b**) we were permitted to cut a slice from the base

a

b

Fig. 7.4 a and b (a) A 4.46 ct chrysoberyl from Sri Lanka showing rectangular four-rayed asterism. (b) A 13.46 ct chrysoberyl from Sri Lanka showing oblique four-rayed asterism. Photographs by courtesy of M. P. Steinbach, Idar-Oberstein.
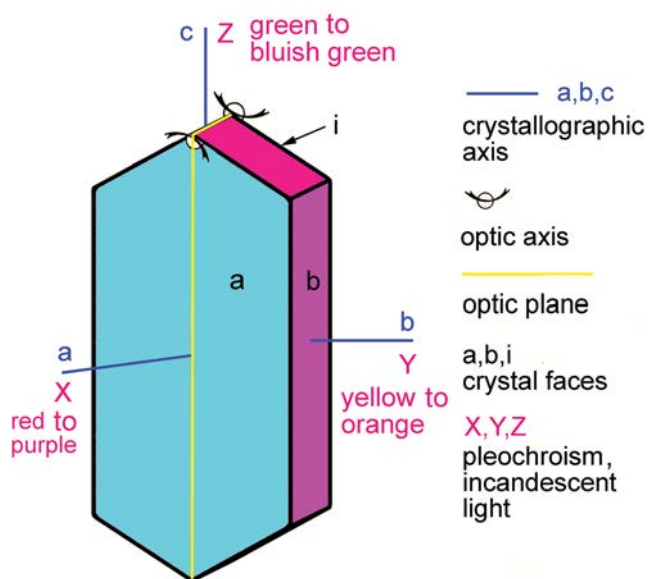
Fig. 7.5 a Orientation of the optic plane and the optic axes relative to the crystallographic axes a, b and c in optically biaxial chrysoberyl; the optic plane is represented by the ac-plane; the pleochroism of X, Y and Z for the chromium-bearing chrysoberyl variety alexandrite with X || a, Y || b and Z || c in incandescent light as observed under the immersion microscope is indicated in the figure. Crystal drawing and artwork by K. Schmetzer.
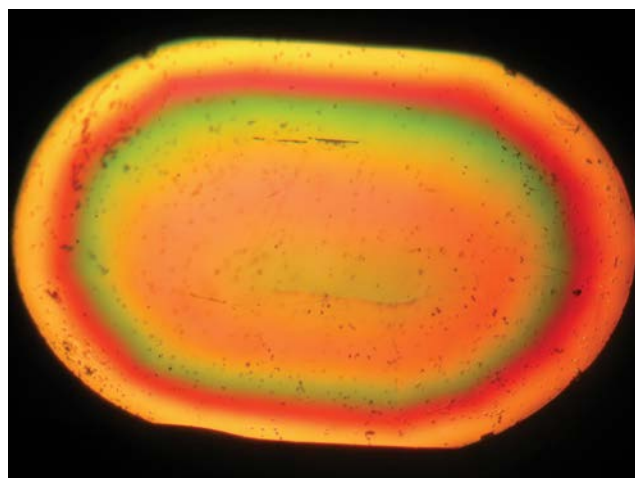

Fig. 7.5 b Interference figure of alexandrite, view slightly inclined to one of the optic axes. Tilting the crystal towards a position in which the optic axis is parallel to the direction of view moves the interference rings towards the centre of the sample. Consequently, a procedure which includes a search for the interference figures of both optic axes can be used to determine the crystal orientation of faceted samples by optical means. Immersion, crossed polarizers, 30x. Photograph by K. Schmetzer.

of the cabochon. From this transparent slice it was possible to determine the orientation of the optical axes and using this information and, knowing the orientation of the slice relative to the asteriated chrysoberyl cabochon, it was possible to determine the orientation of light bands. The results were consistent with those of the other sample described, the needles causing the somewhat stronger light band were oriented parallel to the a-axis and a second set of needles or needle-like particles was oriented in a direction perpendicular to the a-axis, i.e. in the b-c plane, most probably parallel to [011].

For one of the two other samples with somewhat weaker four-rayed stars, the author was not able to determine the orientation of the light bands relative to the crystallographic axes by optical methods because the sample was only partly translucent. The other available sample showed a combination of a light band of an ordinary cat's-eye and a somewhat diffuse reflected light band caused by reflection from minute fluid inclusions in plane fissures.

Consequently, the results obtained from these two chrysoberyls with the most intense stars confirm the observations reported in faceted alexandrites from Sri Lanka. Four-rayed asterism in our two samples with the most intense stars is caused by two sets of needles, parallel to the a-axis and parallel to a second direction in the b-c plane, most probably parallel to [011].

Alexandrite crystal group in phlogopite matrix from the Malysheva Mine and shown in both daylight and incandescent light. Fersman Mineralogical Museum, Moscow, Russia. The crystal group measures about 5 x 8 cm and was donated to the museum in 1980. Photograph by K. Schmetzer.

Comparison of growth patterns of Russian, other natural and synthetic alexandrites

Karl Schmetzer

The most commonly observed crystal forms of Russian alexandrites are the dipyramid **o** and the pinacoid **a**. These faces were also seen in many faceted samples as part of the observed internal growth pattern and reflect the external morphology. These two faces, **o** and **a**, are commonly observed in the growth pattern of natural alexandrite from sources other than Russia and in the growth pattern of flux-grown synthetic alexandrite.

A single crystal of alexandrite from Sri Lanka is pictured in **Fig. 8.1 a**, and a cyclic twin of Russian flux-grown alexandrite is shown in **Fig. 8.2 a**. A growth pattern in a faceted alexandrite from Sri Lanka formed by two dipyramids **o** and **o'**, is shown in **Fig. 8.1 b** whereas a growth pattern with two prism faces **a** and two dipyramids **o** as observed in Russian flux-grown alexandrite is shown in **Fig. 8.2 b**. From this it can be seen that the identification of **a** and/or **o** faces in the growth pattern of an alexandrite sample of unknown origin does not permit either origin determination or the distinction of natural from synthetic samples.

In many Russian alexandrites there is a characteristic growth pattern of two dipyramids **w** in combination with other faces such as **i**, **o**, and **a**. The author has not seen this type of growth pattern in samples from other localities. A complete description of growth patterns and inclusions of alexandrite from all other sources is not possible within this study but it is known that characteristic differences exist. Sri Lankan samples for example, with

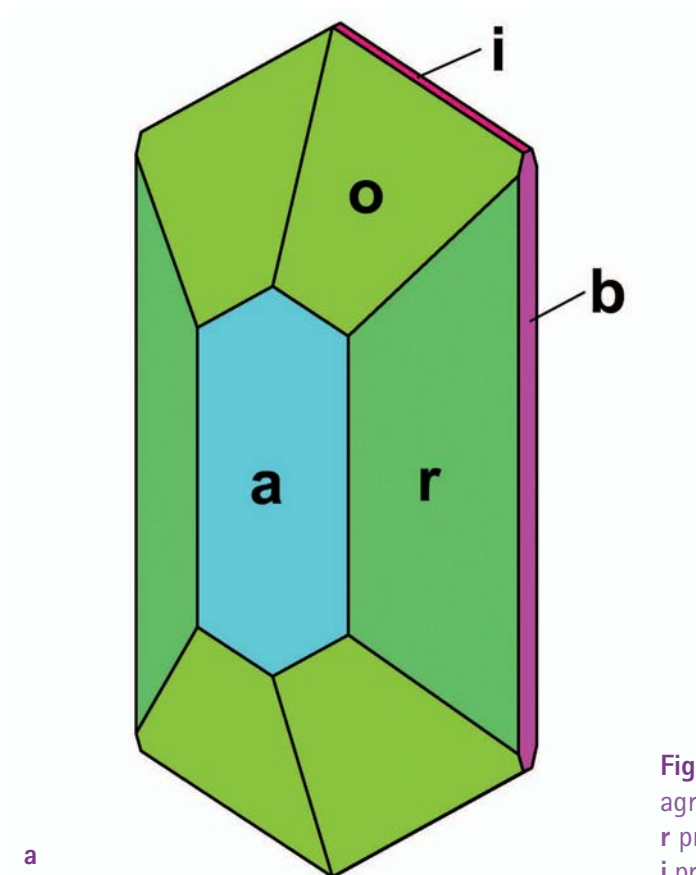**Fig. 8.1 a** Habit of natural alexandrite from Sri Lanka; diagram of a single crystal with dominant **a** pinacoid, **r** prism and **o** dipyramid with subordinate **b** pinacoid and **i** prism faces. Crystal drawing and artwork by K. Schmetzer.
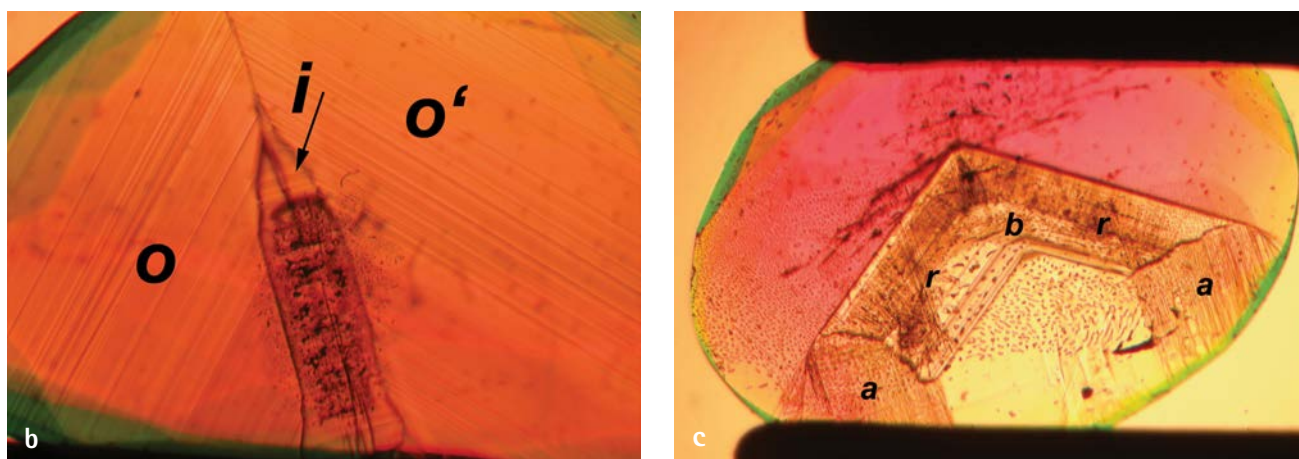
Fig. 8.1 b and c Growth pattern of natural alexandrite from Sri Lanka; (b) Growth pattern in an alexandrite from Sri Lanka; the growth planes are parallel to two **o** dipyramids and parallel to an **i** prism face, 60x. (c) Growth pattern with colour zoning in an alexandrite from Sri Lanka consisting of **a** and **b** pinacoids and **r** prism faces. View parallel to the c-axis, 30x. Photographs by K. Schmetzer.
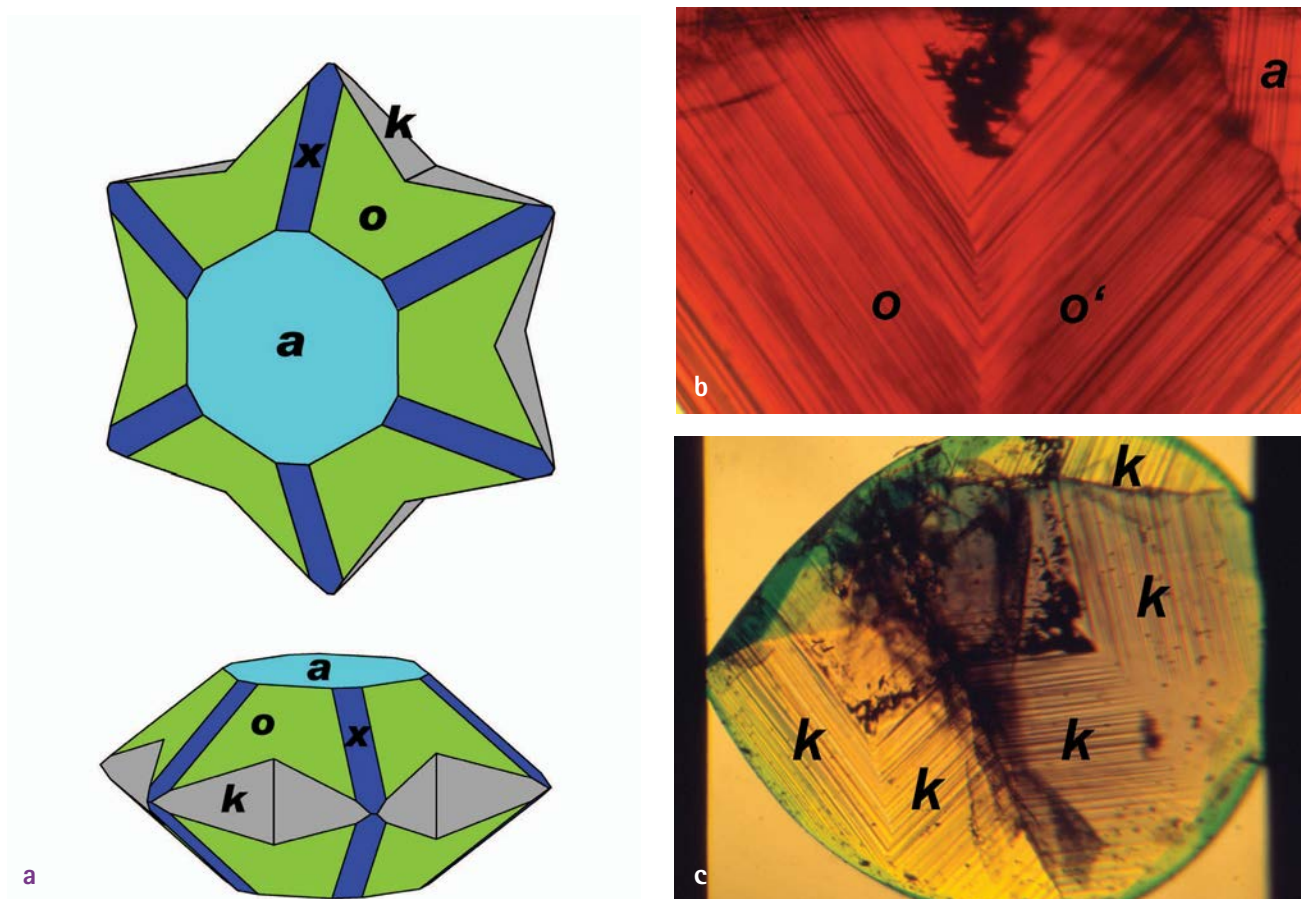
Fig. 8.2 a to c Habit and growth pattern of Russian flux-grown synthetic alexandrite produced in Novosibirsk, Russia; (a) Diagrams of cyclic twins (trillings) with dipyramidal habit; the **a** pinacoid, the **k** and the **x** prisms as well as the **o** dipyramid are shown. Crystal drawings and artwork by K. Schmetzer. (b) Growth pattern in Russian flux-grown synthetic alexandrite; growth planes parallel to two **o** dipyramids and an **a** pinacoid (top right), 50x. (c) Growth pattern in Russian flux-grown synthetic alexandrite; in this cyclic twin growth planes parallel to the **k** prism form characteristic re-entrant angles of 141.5°. View parallel to the a-axis, 45x. Photographs by K. Schmetzer.

Fig. 8.3 a and b Natural alexandrite crystal from Mananjary, Madagascar showing typical habit and growth pattern. (a) Diagram of a single crystal with dominant **a** and **b** pinacoids and **i** prisms as well as subordinate **o** and **m** faces. Crystal drawing and artwork by K. Schmetzer. (b) Characteristic growth pattern of dominant **b** and **i** faces. View parallel to the a–axis, 30x. Photograph by K. Schmetzer.

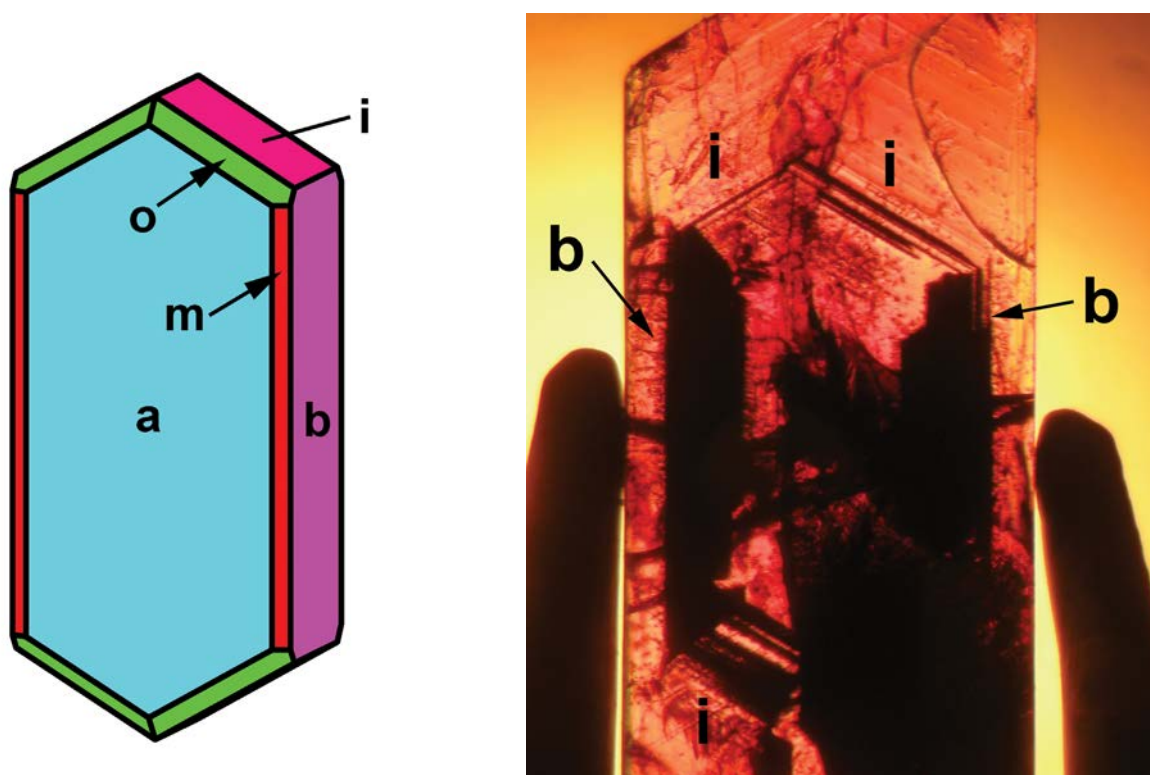their morphology shown in **Fig. 8.1 a**, have growth patterns that sometimes consist of a dominant prism **r** (130) in combination with pinacoids **a** or **b** (**Fig. 8.1 c**). This pattern, with dominant faces **r**, was never observed in Uralian alexandrite. Characteristic angles are given in **Table 3**.

In synthetic alexandrite grown by the flux method in Novosibirsk, the prism **k** (021) and the prism **x** (101) are frequently observed (**Fig. 8.2 a**).[1] This morphology is reflected by a characteristic growth pattern with re-entrant angles of 141.5° observed in a view parallel to the twin

planes (**Fig. 8.2 c**). This type of growth pattern is easily observable and was not seen in natural Uralian samples.

Natural alexandrites from other sources such as Hematita, Brazil and Orissa, India or Mananjary, Madagascar show either small or no dipyramids **o** (**Fig. 8.3a**). Typical growth patterns comprise planes parallel to other dominant crystal faces, e.g. the pinacoid **b** and the prism **i** (**Fig. 8.3 b**).

This suggests that growth zoning could also provide a negative indication of provenance. The absence of a particular growth pattern, for example, zoning parallel to the **o** faces, may indicate the specimen is not Uralian.

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[1] See Schmetzer et al. (1996).

The Museum für Naturkunde, Berlin, hosts this group of alexandrite crystals-in-matrix that were originally present-ed to Gustav Rose by the Saint Petersburg Mining Institute. Sample size approximately 7 x 8.5 cm. (a) Daylight views. Photograph by K. Schmetzer. (b) Incandescent light view. Photograph by Hawja Götz, by courtesy of the Museum für Naturkunde, Berlin.

Colorimetric data of Russian alexandrite and yellowish green to green chrysoberyl

Karl Schmetzer and George Bosshart

9.1 The three–dimensional CIELAB colour space and colorimetric parameters

Colorimetric systems are used for the quantitative description and prediction of colour phenomena. For the description of colour, special colour coordinate systems, known as colour spaces, were developed.

Many colour systems used today correlate with the uniform CIE L* a* b* colour space (CIELAB colour space), published in 1976 by the Commission Internationale de l'Éclairage (CIE, International Commission on Illumination). The CIELAB colour space is the most complete colour model conventionally used to describe colours and colour differences visible to the human eye. The term 'uniform' indicates that equal distances in the colour space ideally equate to equally perceived colour differences as seen by the standard observer. The three-dimensional CIELAB colour space (**Fig. 9.1**) shows lightness/darkness along the vertical axis (L*). This space is conventionally projected parallel to L* onto a two-dimensional horizontal plane with redness/greenness along a first axis (a*) and blueness/yellowness along a second axis (b*), running perpendicular to a*. The colours related to this rectangular coordinate system are (**Fig. 9.2**):

+ a*-axis: red purple   + b*-axis: yellow
– a*-axis: bluish green   – b*-axis: blue

The parameters a* and b* are also expressed as hue angle h_{ab} and chroma C^*_{ab}, which alternatively may be designated as saturation (**Fig. 9.2**). The hue angle h_{ab} is measured in degrees and ranges from 0° to 360° starting with h_{ab} = 0° at the +a* axis and increasing counterclockwise. Chroma C^*_{ab} represents the distance of a sample locus from the origin of the a*b* plane. Hue angle h_{ab} and chroma C^*_{ab} are calculated from a* and b* values as follows:

▶ h_{ab} = arctan (b*/a*) and
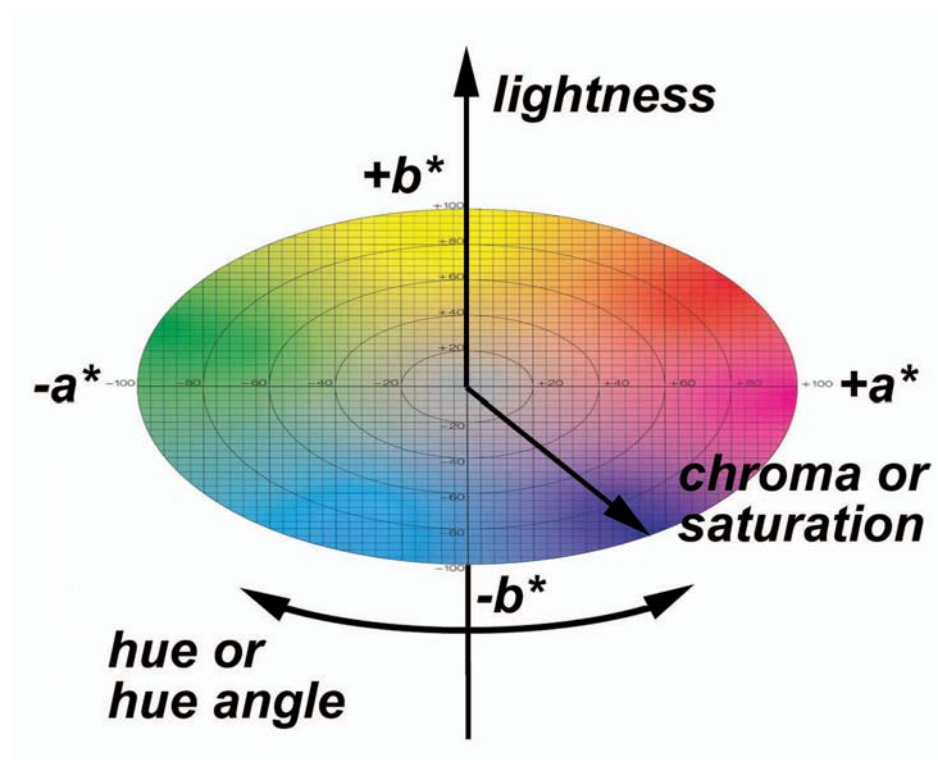▶ C^*_{ab} = (a*^{2} + b*^{2}) $^{1/2}$

Fig. 9.1 General outline of the three-dimensional CIELAB colour space; the principal parameters representing a specific colour are hue or hue angle (h_{ab}), chroma or saturation (C^*_{ab}) and lightness (L*). Artwork by K. Schmetzer.
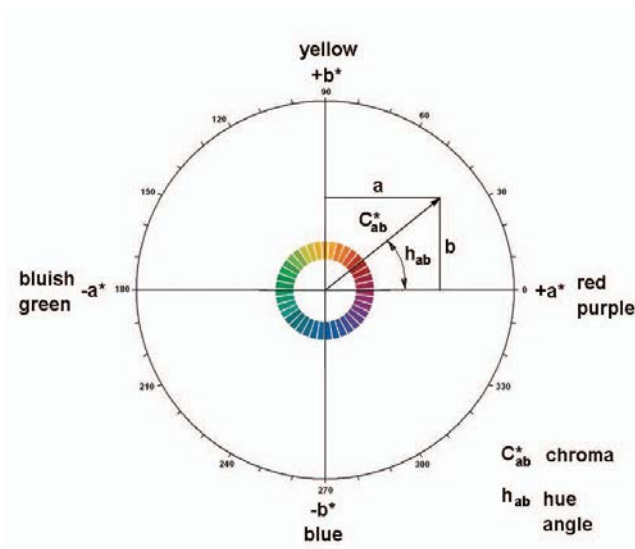
Fig. 9.2 Geometric representation of hue angle and chroma relative to the a*b* plane (the rectangular a*b* coordinate system) of the three-dimensional CIELAB colour space; the third parameter lightness L* (the third axis of the coordinate system) is perpendicular to the a*b* plane; a and b are the coordinates of a sample locus.
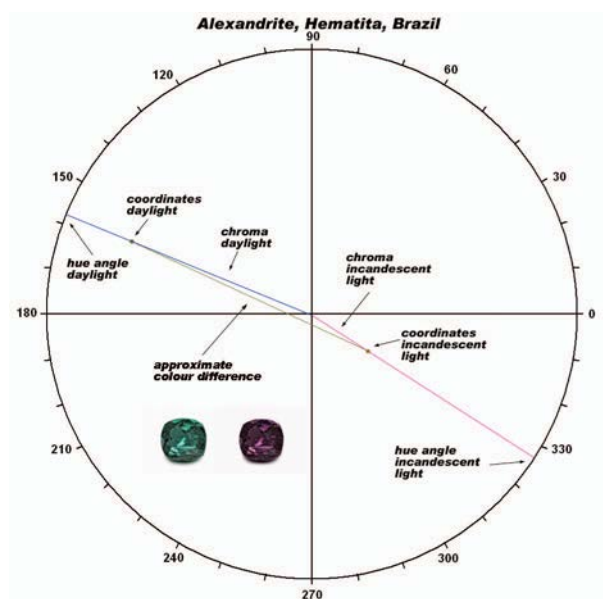

Fig. 9.3 Colorimetric parameters of an alexandrite from Hematita, Brazil in the CIELAB colour space.

The distance between the two loci of one sample in the three-dimensional CIELAB colour space for two different light sources (illuminants) is represented by the parameter ΔE^*_{ab}. Furthermore, the hue angle difference Δh_{ab} is a frequently used parameter to characterize the extent of colour change for a specific pair of illuminants, such as D_{65} for daylight and A for incandescent light.

Quantitative data for colour difference and hue angle difference between two sample loci, I and II in the CIELAB colour space are easily obtainable as follows:

▶ The colour difference ΔE^*_{ab} is calculated as

$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{\frac{1}{2}}$

where ΔL^*, Δa^* and Δb^* represent the difference between the L*, a* and b* values of the two points I and II, respectively.

▶ The hue angle difference Δh_{ab} is calculated as

$\Delta h_{ab} = h_{ab}(\text{point I}) - h_{ab}(\text{point II})$.

Colour differences ΔE^*_{ab} of less than 1 CIELAB units are practically invisible, differences above 3 CIELAB units are clearly recognizable. Hue angle differences of less than 10° are difficult to observe.

The colorimetric data of a faceted alexandrite from Hematita, Brazil in the CIELAB 1976 colour space are given as an example in **Fig. 9.3**. The parameters were calculated as follows:

▶ Coordinates for daylight D_{65}: L* = 56.82; a* = -14.95; b* = 6.01

▶ Further parameters for daylight D_{65}: chroma C^*_{ab} = 16.11; hue angle h_{ab} = 158°; colour: green

▶ Coordinates for incandescent light A: L* = 55.54; a* = 4.58; b* = -3.07

▶ Further parameters for incandescent light A: chroma C_{ab} = 5.51; hue angle h_{ab} = 326°; colour: purple

▶ Colour difference ΔE^*_{ab} = 21.56; hue angle difference Δh_{ab} = 168°

Fig. 9.4 illustrates a specially developed colour wheel that shows the dependency of hue angles and colours. In this illustration colours with high chroma are arranged at hue angle distances of 10° each although for practical use it was desirable to have intermediate colours at hue angle differences of 5° available for the yellow to orange range.[1]

For further details, especially for the detailed mathematical algorithms needed for the calculation of coordinates in various colour spaces from spectroscopic data, the reader is referred to standard textbooks or treatises on

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[1]   For this colour wheel, the names of the colours were taken from Schmetzer et al. (2009).
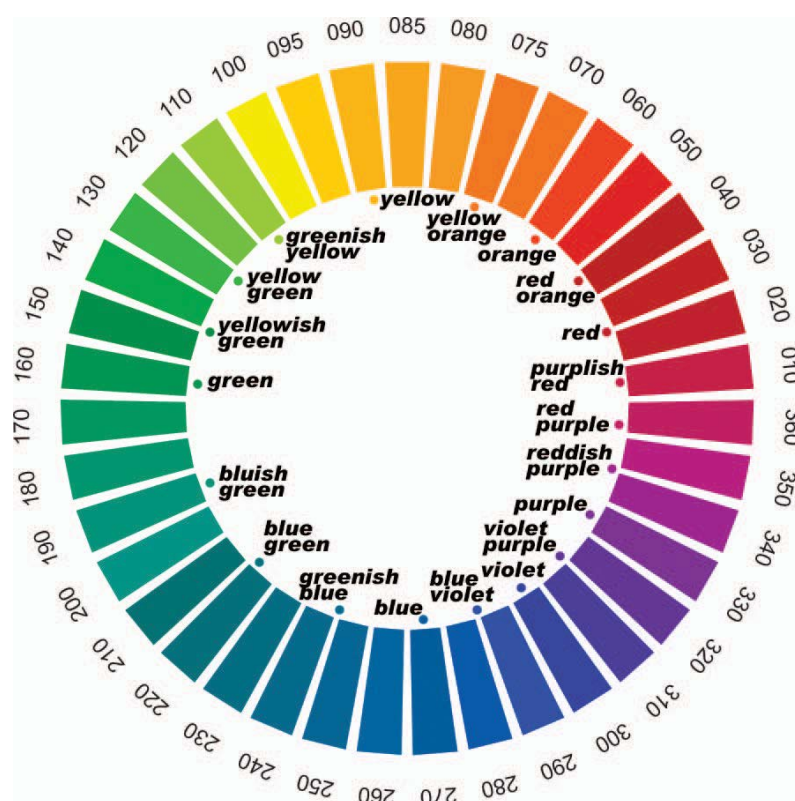
Fig. 9.4 Hue circle or colour wheel of the CIELAB colour space representing examples of colours at different hue angles of the three-dimensional colour solid at high chroma and lightness 50. Copyright dtp studio Oldenburg and RAL gGmbH, Sankt Augustin, Germany, reproduced by permission. Examples for the verbal designation of colours in the present paper are also shown.

colour and colorimetry.[2] A text describing the CIELAB colour space for gemmological applications was published by Liu and Hurwit in 2008, and a detailed treatise of colorimetric parameters for colour-change garnets from Madagascar is also available.[3]

9.2 Materials and methods

The visually observable colouration of alexandrites and chrysoberyls is not only dependent on the change of illuminants from daylight to incandescent light, but is also very sensitive to different types of natural light; direct sunlight, diffuse light from cloudy skies, light of the blue sky in the northern hemisphere, morning, noon, or evening light. The colour temperature of daylight depends on geographic location, time, date, and atmospheric conditions, and is mostly in the range of 5500 to 6500 K. Because of these variations it is desirable to correlate and confirm the results of visual colour observation and compare them with colorimetric measurements.

D_{65} is an artificial daylight with an ultraviolet component that is designated "standard noon daylight" with a colour temperature of approximately 6500 K whilst A is tungsten light with a nominal colour temperature of 2856 K. According to their spectral power distribution, both are the best suited, standardized substitutes for the two traditional natural light sources: diffuse daylight and candle light. D_{65} is produced by xenon lamps with the UV component partly filtered and is widely used in simultaneously recording spectrometric systems whilst A is simulated by tungsten-filament bulbs or by tungsten-halogen lamps and is used in sequentially recording spectrometers. Both D_{65} and A have widespread uses in the industry, such as in GretagMacbeth colour viewing booths.

In general, colorimetric parameters can be determined from each absorption spectrum. Specially designed

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[2] See, e.g., Wyszecki and Stiles (1982); CIE (1986, 2004); Richter (1996); Kuehni (1997); Hunt (2004); Ohta and Robertson (2005); MacEvoy (2005).
[3] Schmetzer et al. (2009).

Fig. 9.5 Faceted 7.95 ct Russian alexandrite with colour change shown from green in daylight to reddish purple in incandescent light. Sample belongs to group B of the present study (see section 9.4). Sourced from the Rudolf Schupp Company, Pforzheim, Germany. Photograph by K. Schmetzer.

spectrophotometers provide software that allows a direct calculation of colorimetric parameters from the spectrum measured. Using this type of instrument, colorimetric and spectroscopic data for 29 faceted chromium-bearing chrysoberyl and alexandrite specimens from the Urals, Russia (**Fig. 9.5, 9.6 a, b, 9.7 a, b**), were measured in transmission mode with a Zeiss multi-channel colour spectrometer, version MCS 311, and a Gemprobe GP 311 integration sphere.

The Zeiss MCS 311 is a double-beam colorimeter equipped with:
▶ a pulsed Xenon lamp housed in a $BaSO_4$-lined integration sphere of 60 mm internal diameter providing diffuse, indirect illumination
▶ Schott quartz-type fibre-light guides

▶ two identical dispersive modules, each with a concave holographic grating and a 512-channel photodiode array
▶ a $BaSO_4$-lined sample platform with a central 3 mm mask hole for light transmission through the sample.

The instrument is designed for (nearly) simultaneous light intensity measurement of sample and reference beams and for colorimetric data processing. The orientation of samples is described below.

Colorimetric data processing was performed with the Zeiss MCS 311 system using the Zeiss DIAMOCR software that instantly provides the CIE 1931 chromaticity values x, y, Y and the CIELAB parameters L*, a*,b*, hue angle h_{ab} and chroma C^*_{ab} for two light sources D_{65} (daylight) and A (incandescent light). These values are based on the absorption spectrum recorded from 375 to

Fig. 9.6 a and b Chrysoberyl and alexandrite from the Urals show a wide variation of colours in both daylight and incandescent light. Although all samples pictured contain distinct amounts of chromium as a trace element, not all samples should be designated alexandrites. The three yellowish green and light green chrysoberyl samples on the left in the top row are greenish yellow or yellowish green in incandescent light. Similarly the more intensely green to bluish green chrysoberyls that are the second and third samples from the left in the bottom row maybe grey in incandescent light. In contrast, the three samples of alexandrite located in the top row, right and the bottom row extreme left and right are green to bluish green in daylight and purple, reddish purple, red purple or purplish red in incandescent light. Samples with a bright colouration under both light sources are rare. Sample weights are from 0.30 ct (bottom row, third from the left) to 0.60 ct (top row, left) from the reference collection of the Gübelin Gem Lab, Lucerne, Switzerland. Photographs by K. Schmetzer.
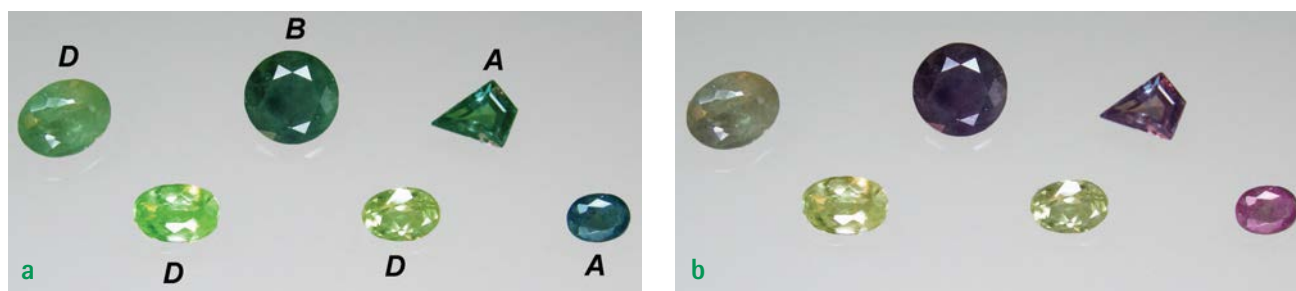
Fig. 9.7 a and b Chrysoberyl and alexandrite from the Urals show a wide variation of colours in daylight and incandescent light. Although all samples pictured contain distinct amounts of chromium as a trace element, yellowish green (bottom row left and centre) and green chrysoberyl (top row left) are greenish yellow or grey in incandescent light whereas green to bluish green alexandrite changes colour to purple, reddish purple, red purple or purplish red in incandescent light. Samples from 0.38 ct (bottom row right) to 1.84 ct (top row centre). Samples sourced from the Rudolf Schupp Company, Pforzheim, Germany. Photographs by K. Schmetzer.

774 nm at 10 ms integration time, 0.8 nm spectral pixel spacing, 2.4 nm spectral resolution, and ≤ 0.1 nm wavelength accuracy and reproducibility.

In order to evaluate the influence of sample orientation a synthetic Czochralski-grown alexandrite crystal was examined. This sample was cut as a cube with the orientation of the edges of the cube exactly parallel to the crystallographic axes a, b and c. The deviation from the ideal orientation was compared with that of the optical axis under the immersion microscope and was found to be less than 5°. The lengths of the edges of the cube varied from 9.0 mm to 9.2 mm, and consequently, the path lengths of the primary light beam in different directions were almost identical. Chemical examination of the sample by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)[4] gave as average values of

three analyses for this sample: V_2O_3 0.09 wt%, Cr_2O_3 0.21 wt%, Fe_2O_3 < 0.01 wt%.

In addition to the Russian specimens mentioned above, about 30 faceted natural and synthetic alexandrites from different occurrences and different producers were examined, taking at least two spectra from different orientations. Routinely, each sample was placed with its table facet on the aperture of 3 mm diameter, with the primary beam entering the sample through the pavilion. The influence of sample orientation was evaluated in two steps:

▶ after rotation of each sample through an axis perpendicular to the table facet and

▶ placing a larger pavilion facet on the aperture with the primary beam entering through different crown facets as well as the table.

9.3 Dependence of colour change on sample orientation

The colours of the synthetic Czochralski-grown alexandrite cube in directions parallel to the three crystallographic axes (a, b and c) as well as the pleochroic colours in polarized light (X, Y and Z) are given in **Table 4**. Colorimetric parameters measured for the alexandrite cube are also listed. In a similar colorimetric investigation of an alexandrite cube performed by Liu et al.,[5] hue angle changes were reported but no values for chroma in daylight and incandescent light were given.

When an orthorhombic chrysoberyl crystal is viewed under polarized light, three colours X, Y and Z can be observed. In a view parallel to the a-axis, the colours for Y and Z can be seen on rotation of the polarizer. This applies as well to observations viewed parallel to b and c under polarized light; X and Z are seen parallel to b and X and Y parallel to c. The colour observed by the unaided eye looking parallel to any one of the three crystallographic axes a, b, and c is always a mixture of two of the X, Y and Z components. More specifically, the colour observed in a view parallel to the a-axis is a mixture of the components Y and Z, parallel to the b-axis it is a mixture of X and Z and parallel to the c-axis it is a mixture of X

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[4] Perfomed by A.-K. Malsy at Gübelin Gem Lab, Lucerne, Switzerland.
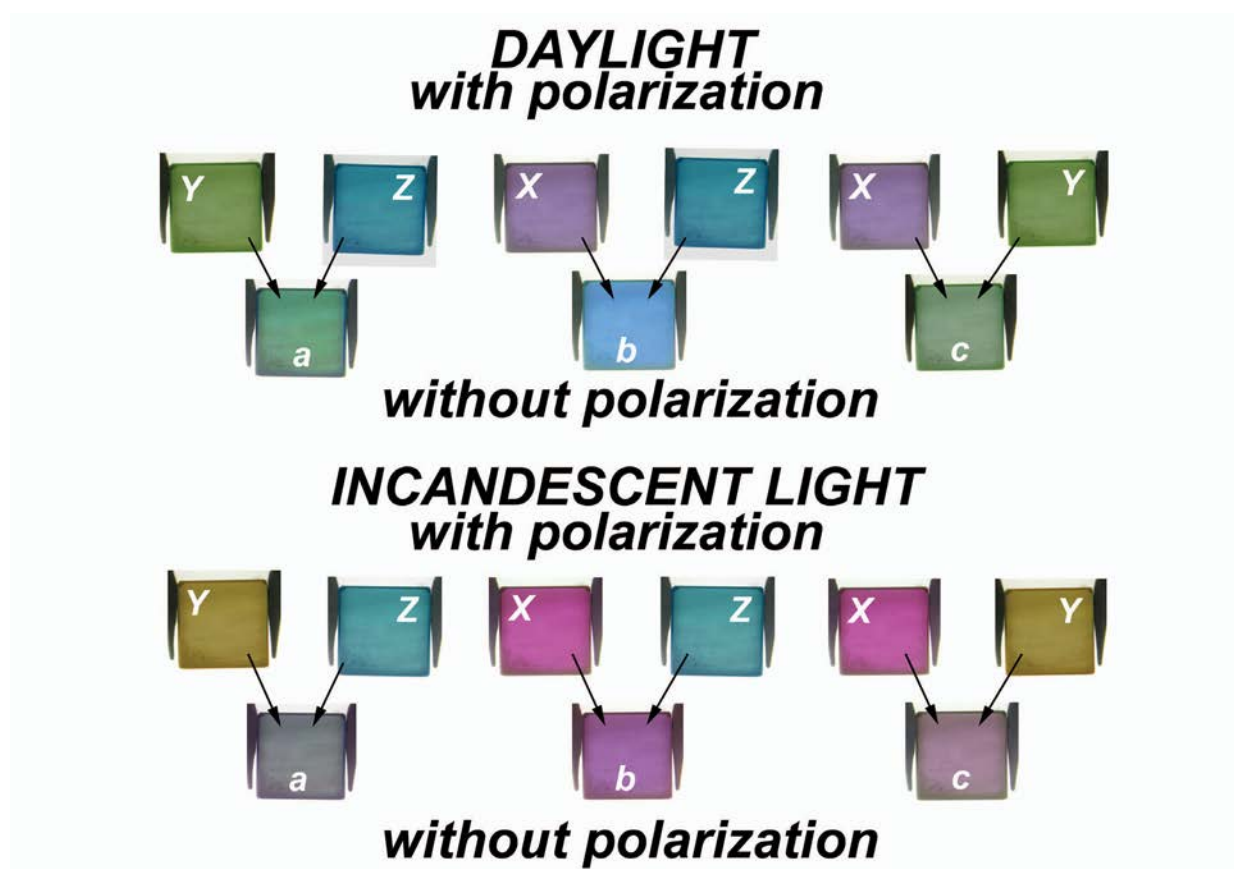[5] Liu et al. (1995).

Fig. 9.8 a Schematic representation of colour and pleochroism in a Czochralski–grown synthetic alexandrite cube in both daylight and incandescent light. With the unaided eye in a view parallel to one of the three crystallographic axes, a, b, or c, the colour is always dependent on two of the three components X, Y, and Z, that are observed with polarized light. Photographs and artwork by K. Schmetzer.

and Y. These changes for the examined alexandrite cube are shown schematically in **Fig. 9.8 a**. The same scheme applies under incandescent light in which two of the three components, X and Y, show a distinct colour change and thus, the colours observed parallel to one of the three crystallographic axes a, b and c also show a distinct colour change (**Table 4 and Fig. 9.8 a**).

Polarized and non-polarized absorption spectra of the cube of synthetic alexandrite[6] viewed in directions parallel to the a-, b-, and c-axes (**Fig. 9.8 b**) show three different polarized spectra X, Y, and Z with strongly pleochroic absorption bands. The non-polarized spectra in all three directions are always composed of the two polarized spectra that were measured in these particular directions of view.

Absorption bands for vanadium and chromium cannot be separated in the spectra of vanadium- and chromi-

um-bearing samples. In synthetic samples containing only one of the colour-causing trace elements, vanadium or chromium,[7] the absorption maxima are located in the same spectral areas (**Fig. 9.8 c**). On the other hand, vanadium- and chromium-bearing chrysoberyls have differing pleochroism. In chromium-bearing samples, the three spectra X, Y, and Z are distinct and three different colours are produced. Whilst in vanadium-bearing samples the Y and Z spectra are similar and differ distinctly from the X spectrum (**Fig. 9.8 c**). It is mentioned that pure vanadium-doped synthetic chrysoberyl shows a colour variation from yellowish green to bluish green in non-polarized light, but no alexandrite-like colour change.

Colorimetric parameters for non-polarized spectroscopic measurement with the primary beam parallel to the three crystallographic axes are given in **Table 4** while colorimetric parameters in the CIELAB colour space are

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[6]   Perfomed by A.-K. Malsy at Gübelin Gem Lab, Lucerne, Switzerland.
[7]   Bukin et al. (1980).

Fig. 9.8 c Polarized spectra of vanadium and chromium doped synthetic chrysoberyl and alexandrite; both types of spectra show two dominant absorption bands in the visible range, the chromium spectra indicate a more intense pleochroism compared to the vanadium-bearing sample; after Bukin et al. (1980).
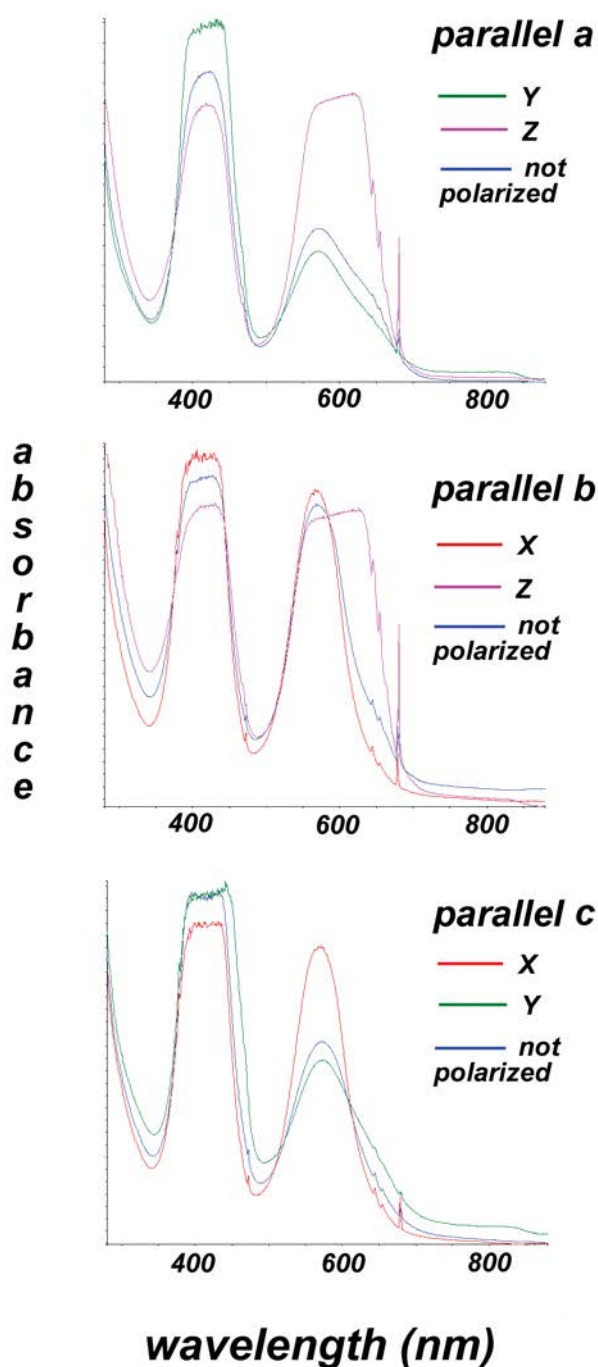
Fig. 9.8 b Polarized and non-polarized spectra of a Czochralski-grown, vanadium- and chromium-bearing synthetic alexandrite cube in views parallel to the three crystallographic axes, a, b, or c; the spectra taken without polarized light represent a mixture of the two polarized spectra (X, Y, or Z) taken in the same orientation.

duces distinct differences. The hue angle difference between daylight and incandescent light is at its maximum for the direction parallel to c and distinctly smaller for measurements parallel to a and b. In daylight, the view parallel to a produces the highest chroma, indicating that this direction gives the most brilliant green. In contrast, in incandescent light, the colour parallel to a is a less attractive bluish grey. The hue angle change between daylight and incandescent light is largest for the direction parallel to c and, in this direction, the colour is light green in daylight and a light greyish purple in incandescent light. In the direction parallel to b, the colour changes from greenish blue to an intense red purple with high chroma.

Consequently, there is no ideal orientation for the desired combination of high chroma in both daylight and incandescent light, together with high hue angle change. This is one of the reasons to explain why alexandrites that show an attractive bright green or bluish green colour in daylight as well as a bright purple colour in incandescent light are rare. This fact is mentioned in many gemmological textbooks. Gem cutters know that the best green

plotted in **Fig. 9.9**. From these it can be clearly seen that different measurements taken through two parallel faces of the cube result in minor variations. In contrast, measurement through the other parallel faces of the cube pro-
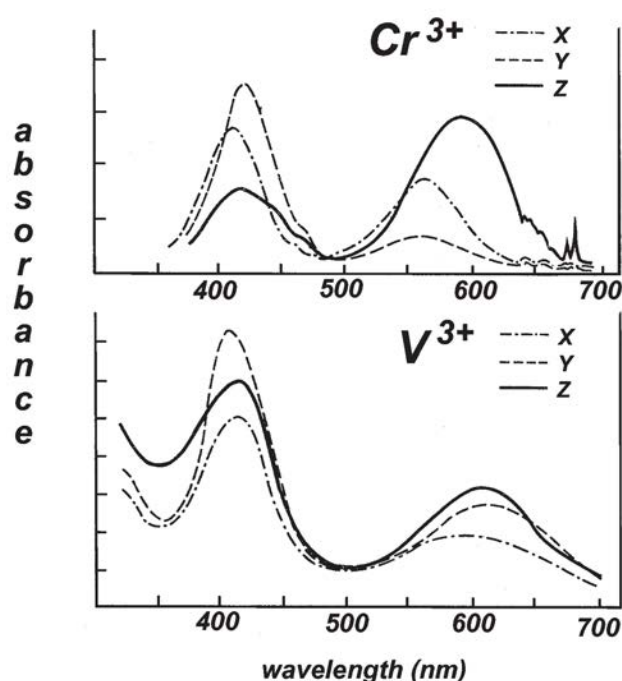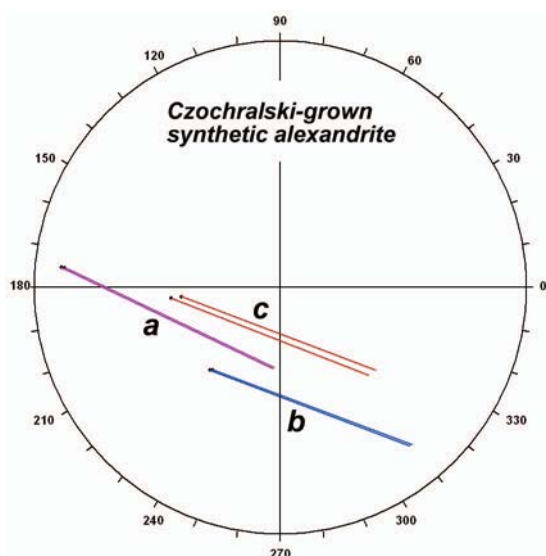
Fig. 9.9 Colorimetric parameters of a Czochralski-grown synthetic alexandrite cube in both daylight and incandescent light. Measurements in two parallel directions perpendicular to parallel faces of the cube show only small observable differences between the colour loci. The distance from the centre of the coordinate system represents the chroma in the direction of measurement. In daylight chroma is maximal for a view parallel to a, and in incandescent light chroma is maximal for a view parallel to b. For measurement in the c direction, the largest hue angle change is observed.

Fig. 9.10 Examples of colorimetric parameters for faceted natural and synthetic alexandrites; each sample was measured in non-polarized light in slightly different orientations against the primary beam of the spectrometer entering either through the pavilion or through the crown of the samples. The bars between the colour loci in daylight and incandescent light for different measurements of one sample are almost parallel to each other and show only a small shift parallel to the a*- and b*-axes of the CIELAB coordinate system.

colouration in daylight is obtained with an orientation of the table facet parallel to the **a** pinacoid and perpendicular to the a-axis. However, a better colour change and a better colouration in incandescent light are obtained [8] when the orientation of the table facet is parallel to the **b** pinacoid and perpendicular to the b-axis. For single crystals, a good colour change is also produced when the table facet is perpendicular to the c-axis.

For twins or trillings, the a-axes of the different individuals are parallel and, as a result, the orientation of the table facet parallel to the **a** pinacoid gives the best colour in daylight. In a view perpendicular to the **a** pinacoid, all twins and trillings reveal crystals in different orientations and, therefore, the observed colour is always a mixture of the colouration parallel to the b- and c-axes of component single crystals. Thus, to obtain a good colour change and high chroma for incandescent light, table facets should be orientated perpendicular to the **a** pinacoid.
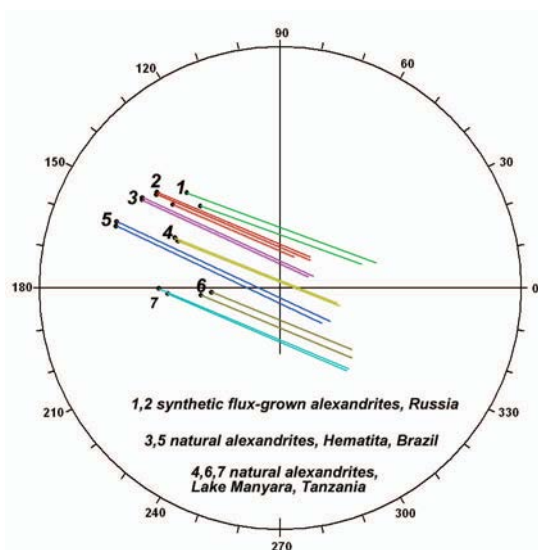
These conclusions are not consistent with the data of Liu et al. Most probably, the crystallographic orientation of their examined cube of synthetic alexandrite was not consistent with the crystallographic orientation of their natural alexandrite single crystal and alexandrite trilling.

To avoid the disadvantages caused by the pleochroism of chromium-bearing chrysoberyl, some faceted alexandrites were manufactured as composite gems by assembling two pieces of synthetic alexandrite in different crystallographic orientations.[9] Although this method might improve the situation for synthetic alexandrite, it is not practical for expensive natural alexandrite crystals, as the final product would be a doublet or even a triplet, and considered as an assembled gemstone.

Although alexandrite shows distinct pleochroism (trichroism) in polarized light as described above, the orientation of samples for colorimetric measurement using non-polarized light is not critical. **Fig. 9.10** shows a plot

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[8]   See Fischer (1954).

[9]   Morris and O'Dell (1981).

of sample loci of natural and synthetic alexandrites in daylight and incandescent light. Measurements were made on a single sample in different orientations with the primary beam entering through the crown or pavilion. For each of the samples measured in the different orientations as mentioned above, the admixture of the three basic colours X, Y, and Z in different proportions, according to the orientation of the sample, causes a parallel shift of the connecting line between sample loci in daylight and incandescent light. This means that, under the measuring conditions described above, the orientation of the sample has an almost negligible influence. Furthermore, the colorimetric data obtained clearly rep-

resented the visually observed face-up coloration of the alexandrites.

Thus, a single measurement in non-polarized light with the sample in face-down alignment is sufficient for a reliable determination of the colorimetric parameters for a faceted gemstone. However, a second or even third measurement, taken in different orientations with the primary beam entering through the crown or pavilion is recommended for control. It should be emphasised that the colorimetric data would show differences as described above for the alexandrite cube, if the sample is examined at right angles to the table facet.

9.4 Distinction of alexandrite from yellow to green colour–change chrysoberyl

The absorption spectra of all 29 measured chrysoberyls and alexandrites from the Urals showed distinct absorption bands of iron and chromium of variable intensities. These results are consistent with chemical investigations by X-ray fluorescence spectroscopy and LA-ICP-MS.[10] There are numerous papers describing the absorption spectra of natural and synthetic alexandrite, the assignment of absorption maxima to chromium and iron related absorption bands as well as the distribution of chromium and iron between the two relevant aluminium sites of the chrysoberyl lattice.[11]

It is evident that the colour of a faceted alexandrite is a complex function of at least three basic parameters:

▶ the concentration of colour-causing trace elements, mainly chromium and iron, occasionally also vanadium, and their distribution between different lattice sites

▶ the orientation of the table facet relative to the crystal axes

▶ the thickness of the sample, which determines the variable path length of light travelling through the faceted gemstone.

However, the characterisation of colour in a faceted gemstone as described below is based on spectroscopic

measurement and the colorimetric evaluation of spectroscopic results.

According to visual colour estimations in daylight and incandescent light combined with colorimetric parameters, the samples can be divided into 5 distinct groups labelled A to E. The colours in daylight and incandescent light together with the main colorimetric parameters are summarized in **Table 5**. The sample loci are plotted in the a*b* plane of the CIELAB colour circle in **Fig. 9.11 and 9.12**.

The colour difference ΔE^*_{ab} in the three-dimensional CIELAB colour space and the hue angle difference Δh_{ab} in the CIELAB colour circle are graphically presented in **Fig. 9.13**. The five preselected sample groups with their various extents of colour change are individually notated as demonstrated in **Fig. 9.13**.

The colorimetric parameters calculated for all spectra of the 29 examined samples show a minimal change in lightness for different illuminants. Consequently, for these samples, the graphic representation in the a*b* plane of the CIELAB colour circle (**Fig. 9.11 and 9.12**) shows the characteristic change for the three-dimensional CIELAB colour space. In other words, the length of the line connecting the two loci of one sample in the a*b* plane and the direction of this line are a good graphic representation of the colour difference ΔE^*_{ab}.

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[10] See chapter 10.

[11] See, e.g., Farrell and Newnham (1965); Hassan and El-Rakhawy (1974); Walling et al. (1979); Schmetzer et al. (1980); Powell et al. (1985); Rager et al. (1998); Rabadanov and Dudka (1998); Pinheiro et al. (2000); Yeom and Choh (2001); Weber et al. (2007).
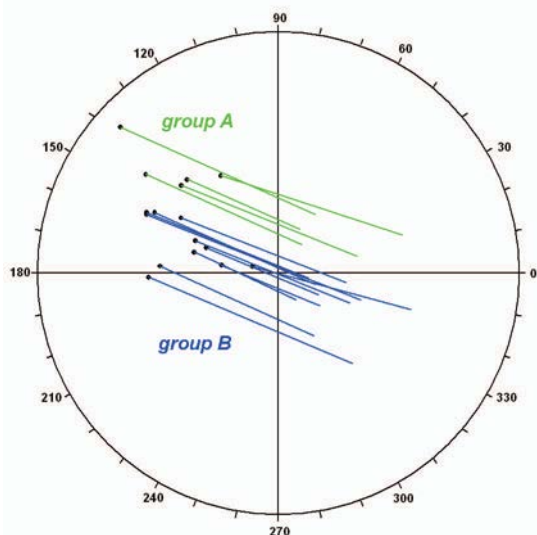
Fig. 9.11 Colorimetric parameters for Russian alexandrites (groups A and B) in the CIELAB 1976 colour circle; the neutral point (white point) is in the centre of the a*b* coordinate system; the small black circles represent the coordinates for the alexandrites in daylight D$_{65}$ and the ends of the differently coloured bars represent their coordinates for tungsten light A; the outer circle represents a chroma of 22. The typical alexandrite–like colour change from daylight to incandescent light is evident.
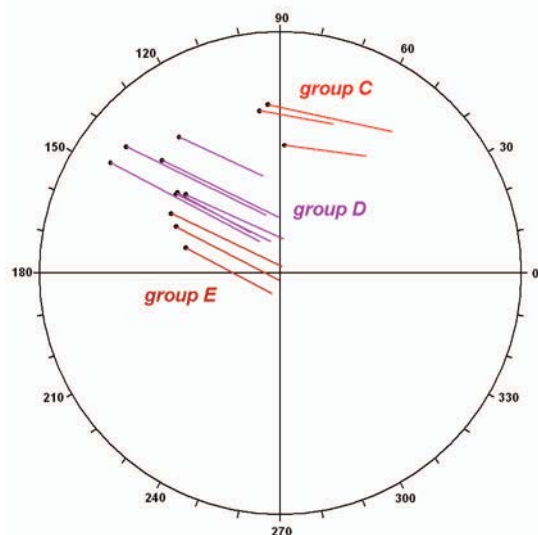
Fig. 9.12 Colorimetric parameters for yellow, yellowish green or green Russian chrysoberyls (groups C, D and E) in the CIELAB 1976 colour circle; the neutral point (white point) is in the centre of the a*b* coordinate system; the small black circles represent the coordinates for the chrysoberyls in daylight D$_{65}$ and the ends of the differently coloured bars represent their coordinates for tungsten light A; the outer circle represents a chroma of 22. The typical alexandrite–like colour change from daylight to incandescent light was not observed in these samples.

All samples show a clearly observable colour change between daylight and incandescent light. As shown by **Fig. 9.5–9.7**, this colour change is caused by an increase of red and blue with the change of light source (illuminant) from daylight to incandescent light. Samples from groups A and B reveal the classic alexandrite colour change from yellow green, green or bluish green in daylight and to violet, purple, red purple, red or orange in incandescent light (**Fig. 9.11**). The extent of colour change for all samples in groups A and B is strong to very strong (**Fig. 9.13**).

Samples of cat's-eyes from group C which show moderate colour change, from yellow to greenish yellow in daylight and orange to yellow orange in incandescent light do not represent the classic alexandrite colour change (**Fig. 9.12**). Their colour in daylight is more yellow than green and consequently these samples are designated yellow chrysoberyl cat's-eyes with moderate colour change.

Samples from group D show a moderate colour change between daylight and incandescent light; this change is strong in samples from group E (**Fig. 9.12**). Although the colour of the group D and E samples in daylight is within the range observed for alexandrites, the increase in red is distinctly less than in samples from groups A and B. Thus, samples from group D are yellow green or yellow in incandescent light whilst those from group E show low chroma in incandescent light and therefore are bluish grey or yellowish grey. Although both groups of samples show a clearly observable moderate to strong colour change between daylight and incandescent light (**Fig. 9.13**), the colour change is different from the classic alexandrite colour change that requires a distinct red component in incandescent light. Thus, these samples should be designated colour-change yellowish green or green chrysoberyls rather than as alexandrites.
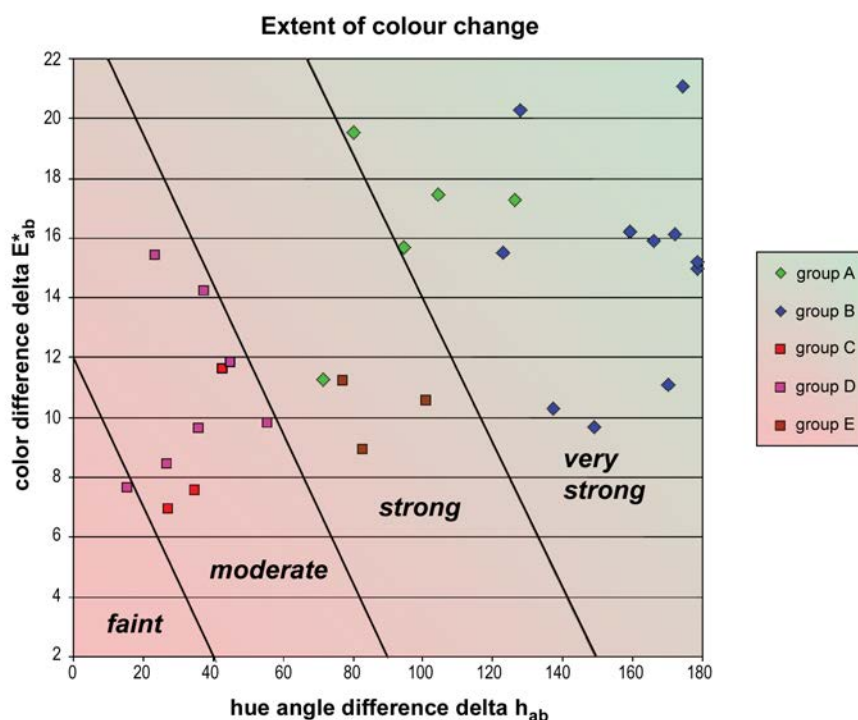
Fig. 9.13 Graph showing the correlation of the main colorimetric parameters of hue angle difference and colour difference in alexandrites and colour-change chrysoberyls from the Urals, Russia, with correlations representing the extent of colour change referred to as faint, moderate, strong and very strong. The extent of colour change for alexandrites (groups A and B) is strong to very strong; the extent of colour change for most yellow to green chrysoberyls (groups C, D and E) is moderate to strong.

9.5 Alexandrite or green chrysoberyl from India – a practical application

Colorimetry is also useful to distinguish green chrysoberyl and alexandrite from sources other than Russia. Morawaka in Sri Lanka followed the discovery of the Uralian alexandrites as the second classic locality for large facetable colour-change alexandrites in the 1880s. Although resources from this locality are now exhausted, both chrysoberyl and alexandrite are known from additional sources in Sri Lanka and India. The states of Orissa and Andhra Pradesh, in India have been a source of both chrysoberyl and alexandrite since the 1990s. For some of this material, there is ongoing discussion in the trade and gemmological laboratories as to a proper designation of these gemstones: alexandrite or chrysoberyl.

The application of colorimetry to solve this gemmological nomenclature problem was demonstrated as follows; a group of 10 faceted samples from India[12] showing a clear colour change from a bright, intense green in daylight to slightly greyish green, almost colourless in incandescent light (**Fig. 9.14 a, b**) were examined. Chemical examination of all samples by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)[13] indicated a very homogeneous trace element pattern consistent with the pattern of material of Indian origin.[14] The ranges of colour causing trace elements were determined as:

▶ V_2O_3 0.08–0.11 wt%, Cr_2O_3 0.09–0.14 wt%, Fe_2O_3 0.41–0.59 wt%, demonstrating comparable amounts of V and Cr.

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[12] Some gem dealers also supplied this type of material and designated its origin as Sri Lanka.
[13] Perfomed by A.-K. Malsy at Gübelin Gem Lab, Lucerne, Switzerland.
[14] See chapter 10.
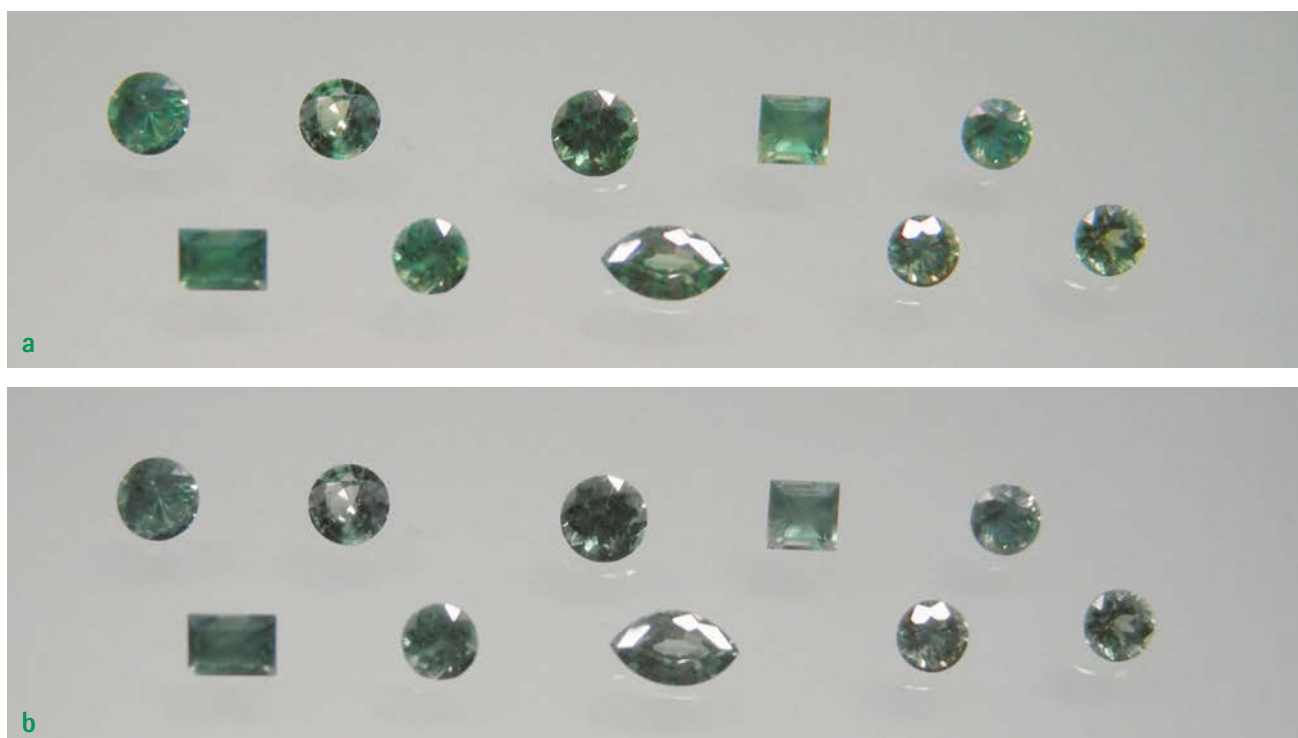
Fig. 9.14 a and b Colour-change chrysoberyls from India show a bright green colouration in daylight and become almost colourless to slightly grey in incandescent light. Sample weights are from 0.14 to 0.23 ct, sourced from Tay Thye Sun, Singapore. Photographs by K. Schmetzer.

Fig. 9.15 V_2O_3/Cr_2O_3 binary diagram showing the variability of these two colour-causing trace elements in natural alexandrite and green chrysoberyl from the Urals, Russia and green colour-change chrysoberyl from India. The chemical data show a clear separation of the source fields of both types of natural chrysoberyl and alexandrite. Chemical data and artwork by A.-K. Malsy, Gübelin Gem Lab, Lucerne, Switzerland.

Fig. 9.16 Colorimetric parameters for colour-change chrysoberyls from India in the CIELAB 1976 colour circle; the neutral point (white point) is in the 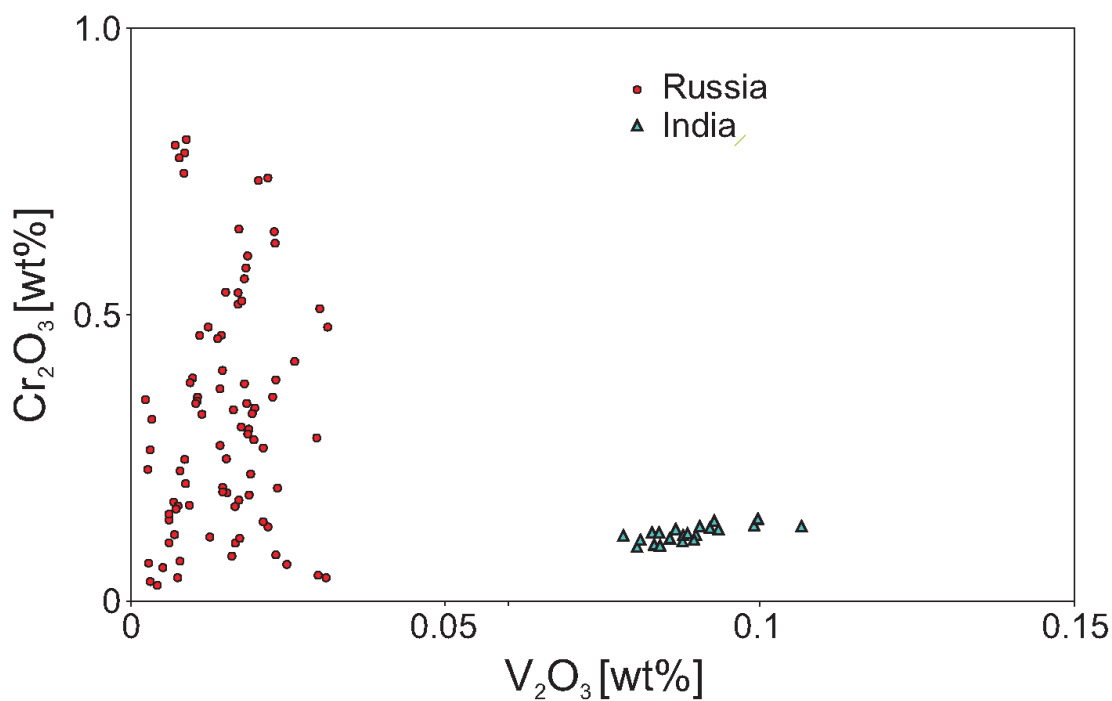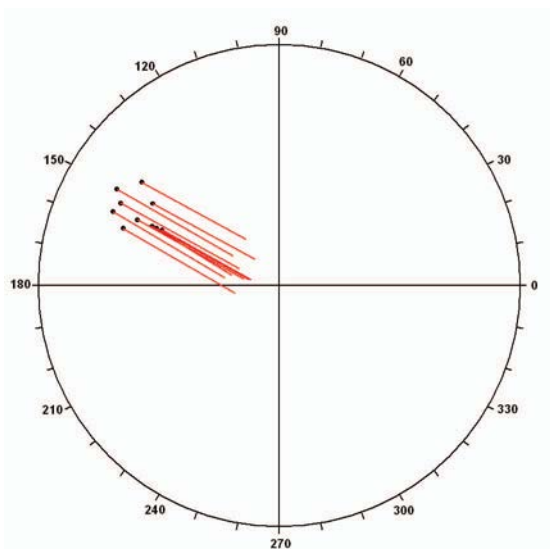centre of the a*b* coordinate system; the small black circles represent the coordinates for the alexandrites in daylight D_{65} and the ends of the differently coloured bars represent their coordinates for tungsten light A; the outer circle represents a chroma of 22. The typical alexandrite-like colour change from daylight to incandescent light was not observed with these samples.

Fig. 9.15 shows a plot of V_2O_3 against Cr_2O_3 for alexandrite and green chrysoberyl from the Urals, Russia and the ten faceted samples from India, pictured in **Fig. 9.14 a and b**. Two distinct fields are apparent; it is evident that this particular type of chrysoberyl from India is coloured by comparable amounts of vanadium and chromium, while in the Russian samples, the influence of chromium is dominant compared to that of vanadium.

The colorimetric data were consistent with visual observation (**Fig. 9.16**). The samples are green with high chroma (saturation) in daylight, but show an extreme light green with low chroma and only small hue angle changes in incandescent light. When changing the light source from daylight to incandescent light, the increase of redness is too small and consequently the samples are only slightly greyish green and do not change to purple or reddish purple. Consequently, it is suggested that this type of material is designated colour-change chrysoberyl rather than alexandrite.

Faceted 1.11 ct oval and 0.87 ct round Russian alexandrites and Canadian diamonds set in platinum, shown in day-light and incandescent light. By courtesy of Warren F. Boyd of R.T. Boyd Limited, Oakville, Ontario, Canada.

10

Trace element chemistry and locality determination[1]

Anna-Kathrin Malsy

10.1 Origin determination in gemmology

The provenance or birth place of a gemstone has always been a matter of interest, not only to gemmological laboratories, but also to the gemstone market. Tumultuous history, exceptional gemstones and their adventures combined with continuous production periods, contribute to the prestige of some particular gemstone deposits. Geographic places such as Kashmir or Burma stand for the most beautiful sapphires and rubies and, as a consequence, they achieve the highest prices in the market. However, the visual appearance and quality of a gemstone can only provide very limited indications of its geographic origin.

Origin determination is basically achieved by comparing all features and properties of an unknown gemstone with those of samples from a fully documented reference collection that includes all relevant mining areas worldwide. The most important gemmological and mineralogical criteria for the characterization of a gemstone are solid and fluid inclusion features, growth structures, the major, minor and trace element composition, and absorption spectra in the UV-Vis-NIR-range. Directly or indirectly, these gemstone properties are always determined by the geological environment in which the stone was formed.[2]

However, the assumption that the determination of origin can be accomplished by the textbook is oversimplified and several complicating factors have to be considered. First of all, with every new discovery of a deposit, there is the possibility of having overlapping characteristics with stones from established occurrences. This is particularly true for sapphires found in Madagascar and Tanzania that have similar characteristics to those from "traditional" occurrences such as Burma or Sri Lanka. Similar geological environments may result in similar characteristics of the gemstone and it requires the captious work of gem testing laboratories to find subtle

distinctive features. Secondly, one should be aware that many gemstones lack the so-called diagnostic inclusions and features that are unique for a specific mine or mining region. Some gemstones are even free of inclusions. In these cases, chemical data provides the most promising basis for distinction between the different geographical origins of gemstones.

In gem testing laboratories, energy dispersive X-ray fluorescence spectrometry (EDXRF) is used as the standard technique for chemical analysis. X-ray fluorescence is a non-destructive method and no time-consuming sample preparation is needed. However, most commercially available instruments are limited in their ability to measure precisely and accurately trace elements in those low concentrations needed for origin determination of gemstones. Furthermore, some light elements cannot be measured at all.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) is one of the most sensitive techniques for trace element analysis of solid materials. It has a wide range of applications in many different fields of science and industry. In recent years LA-ICP-MS has increased in importance in gemmological applications as, in many cases, standard analytical techniques are reaching the limits of their ability. LA-ICP-MS requires the removal of some material from the gemstone by ablation resulting in a shallow laser pit (about $50-100~\mu m$ in diameter), and it is designated a quasi non-destructive method. The LA-ICP-MS allows for the detection of almost all elements from very light, such as lithium, to heavy, such as uranium and from major elements at high concentrations down to ultra-trace elements at concentrations of parts per billion (ppb) levels.

Several studies using LA-ICP-MS as an analytical method for gemstones have been published within the last decade and some are mentioned here. Articles with

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their main focus on origin determination or the characterization of one specific mining region by trace-element chemistry have been published for sapphires, rubies, Paraiba-type tourmalines and emeralds.[3] LA-ICP-MS has also been used on more specific and unique gemmological topics for example, the coating on tanzanite, natural red andesine from Tibet and rare earth elements in yellow danburite from Tanzania.[4] With the increased possibilities offered by LA-ICP-MS to gemmological laboratories, it seems that this field of research interest has been expanded.

10.2 Principles of Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA–ICP–MS)

The principle behind Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) is the use of a high-power laser to ablate small amounts of material from the surface of a sample, which is subsequently analyzed by an ICP Mass Spectrometer. The laser facility serves to collect the sample and introduce it into the ICP-MS unit; this coupling of the ICP-MS with the laser makes this method applicable for gemstones.

Fig. 10.1 is a diagram of a LA-ICP-MS system. The energy provided by a pulsed laser is absorbed by the sample resulting in the release of material as particles, ions, atoms and molecules. Subsequently, the ablated material is transported by a carrier gas into a high-temperature (~ 6000 °C) argon plasma, where particles are completely disintegrated and ionized. A quadrupole mass spectrometer separates the ions by their mass-to-charge ratio (m/z) by setting up a combination of voltages to guide the respective ion of selected m/z to the detector. Although the quadrupole allows only one specific m/z to pass at a time, the very rapid change of voltage settings allows this method to quasi simultaneously detect almost all chemical elements.

The quantitative concentration of an element is determined by comparing the signal intensities to both the intensities of an internal standard element with known concentration and measured intensities acquired on external standard reference materials with known composition such as multi-element glass standard NIST SRM 610.
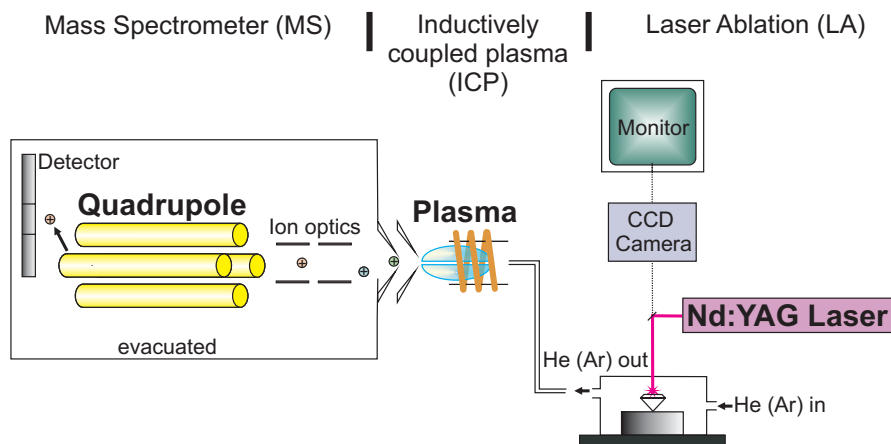
Fig. 10.1 Schematic diagram showing the experimental setup of the LA-ICP-MS facility. The high-energy Nd:YAG laser removes material from the sample surface and transports it to the ICP-MS device by the carrier gas (helium). In passing the inductively coupled plasma (ICP), the sample is disintegrated and ionised. A lens system focuses the ions into the quadrupole mass spectrometer, where they are finally separated by their mass-to-charge ratio and recorded by the detector.

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[3] For sapphires (Guillong and Günther, 2001; Abduriyim and Kitawaki, 2006), for rubies (Saminpanya et al., 2003; Schwarz et al., 2008), for Paraiba-type tourmalines (Abduriyim et al., 2006), and emeralds (Rondeau et al., 2008).

[4] Coating on tanzanite (McClure and Shen, 2008), natural red andesine (Abduriyim and Kobayashi, 2008), danburite from Tanzania (Chadwick and Laurs, 2008).

10.3 Materials and methods

In the present study, 30 gem-quality alexandrite and green chrysoberyl samples from the Tokovaya mining area in Russia and a total of 86 alexandrite samples from other sources such as Hematita, Brazil (13), India (28), Sri Lanka (36) and Lake Manyara, Tanzania (9) were investigated. Samples from Russia included alexandrites with strong colour change from yellowish green, green or bluish green in daylight to violet purple or red purple in incandescent light (groups A and B in chapter 9) and samples that are almost grey or yellowish grey in incandescent light (groups D and E in chapter 9); these should be designated as green chrysoberyl. Some of these samples were rough crystals, a few of the alexandrites were windowed (polished on one or two sides) but most were faceted gemstones ranging from 0.1 to 4.6 ct, from either the Gübelin Gem Lab reference collection or the collection of the senior author (KS). It should be emphasised that the origin research project completed by the Gübelin Gem Lab incorporated alexandrites from additional mining areas in Brazil, Sri Lanka and Tanzania. However the presentation of these results is beyond the scope of the present study, which intends to give an insight into the method used and a simplified model only.

A set of four individual spot analyses, with a laser beam diameter of 100 µm, was performed on each sample.

Table 6 lists the instrumentation and the measuring conditions for the data. With the addition of small amounts of hydrogen (13 ml/min) to the helium carrier gas, there is an increase in sensitivity and therefore lower limits of detection (LOD) were achieved for most elements.[5]

A multi-element glass standard RSM NIST610 was used as the external standard. Data processing and concentration calculations were performed using in-house developed MSExcel spreadsheet based on equations by Longerich et al. (1996). The transient (time resolved) signals for Na, Cu and Pb were observed to decrease from the sample surface downwards, indicating a surface contamination problem. These elements have therefore not been taken into further consideration.

To verify the LA-ICP-MS data for Ca, Ti, V, Cr, and Fe concentrations, electron microprobe analyses were performed using a JEOL JXA8200 instrument. Analytical conditions consisted of an accelerating voltage of 15 kV and a beam current of 20 nA with a10 µm diameter. Data for all elements were corrected using the PRZ method (Phi-Rho-Z).

The results are displayed graphically in **Fig. 10.2 to 10.4**. The individual points represent measurements on various alexandrites; multiple analyses of different spots on the same crystal are plotted separately.

10.4 Trace element content of Russian alexandrites and green chrysoberyls

Table 7 summarizes concentrations for some of the elements that were determined. Other elements have values below the detection limit or are not relevant for the exemplary model presented here.

The values for V, Fe, Cr and Ga are in good agreement with most published data for Russian alexandrites.[6] However, other literature presents data giving significantly higher V concentrations, as well as individual higher values for Cr and Fe.[7] The comparison of data obtained by electron microprobe analyses and LA-ICP-MS showed a

good agreement with a deviation of <10% for Fe_2O_3, whereas higher deviations were observed for V_2O_3 and Cr_2O_3. The much lower CaO concentrations found by electron microprobe indicates that calcium concentration was affected by interference and the key problem is assumed to be an interference of $^{40}Ar^1H^1H$ and $^{40}Ar^2H^+$ on ^{42}Ca.[8] Therefore Ca concentrations determined by LA-ICP-MS were ignored.

A comparison of the chemical data for alexandrite of groups A and B of chapter 9 and green chrysoberyl of

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[5] Guillong and Heinrich (2007).
[6] Vlasov and Kutukova (1960); Ottemann (1965); Ottemann et al. (1978); Kuhlmann (1983); Weber et al. (2007).
[7] Vanadium (Henn, 1985; Kozlov, 2005), higher values for chromium (Henn, 1985; Kozlov, 2005) and iron (Vlasov and Kutukova, 1960; Kozlov, 2005).
[8] Guillong and Heinrich (2007).

groups D and E of chapter 9 show that the chromophore elements Cr and Fe reach higher concentrations in the alexandrite. However values overlap to a large extent, suggesting that additional parameters affect colour and colour change, for example the orientation of the sample (see chapter 9). Likewise other trace element concentrations overlap and this would not allow the distinction between alexandrite and green chrysoberyl only by chemistry. This lack of variation in trace element content may be traced back to the fact that alexandrite and chrysoberyl are found together in the Tokovaya mining area in Russia. Gallium is homogeneously distributed within all the Russian samples tested and as concentrations are very uniform it qualifies as a significant element in the distinction of Russian alexandrites from other sources.

Tin has long been known as a trace element in alexandrite and the values of the present study (**Table 7**) are consistent with published data.[9] To the knowledge of the author, Ge has not been detected in natural alexandrites to date, but only in flux-grown synthetic alexandrites.[10]

10.5 Separation of Russian alexandrites from other sources

Fig. 10.2 shows a plot of Fe values against Cr. It is interesting to note that Fe_2O_3 concentrations are generally higher than, or close to, the Cr_2O_3 values and only a few samples from Russia and Tanzania contain considerably higher Cr than Fe. The highest Fe contents were determined from Russian alexandrites, but only two samples have values above 1 wt% Fe_2O_3. The highest Cr contents were found in alexandrites from Lake Manyara,
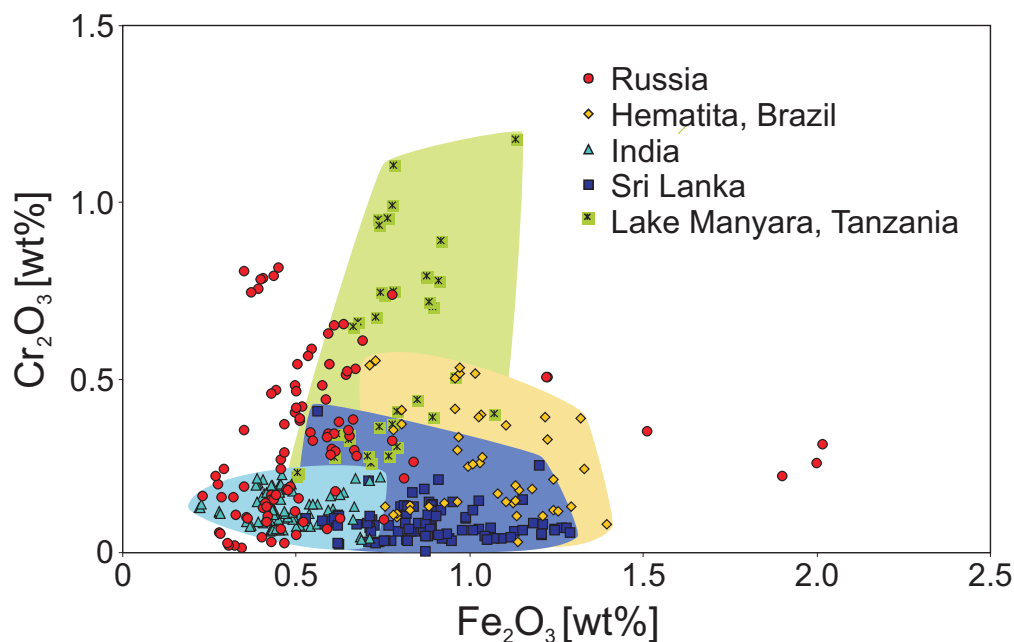

Fig. 10.2 Fe_2O_3/Cr_2O_3 binary diagram showing the variability of the main two colour-causing trace elements in natural alexandrites from different locations. High Fe contents were determined for only a few Russian alexandrites. Most of the samples have concentrations in the range from 0.23 to 0.84 wt% Fe_2O_3 and overlap with data from all other sources. Chromium contents of up to 1.2 wt% Cr_2O_3 were found for some alexandrites from Lake Manyara, Tanzania, but concentration ranges overlap extensively for all sources investigated. The diagram shows that alexandrites from the present sources can not be differentiated by their Fe_2O_3 and Cr_2O_3 contents.

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9   Ottemann (1965).
10   Schmetzer et al. (1996).

Tanzania. It can be seen from **Fig. 10.2** that the results from all five sample groups show the chromophore elements Cr and Fe overlapping and therefore other trace element data are required to identify provenance.

Significant differences are summarised as follows:

▶ After evaluating all elements and different element combinations, B, V, Ga, Ge, Sn and Ta were found to be most relevant for the recognition of Russian alexandrites. In comparison with other sources, Russian alexandrites are characterized by the highest Ge and Ta, high Sn and intermediate B and Ga values (**Table 7**).

▶ The highest Sn values were for samples from Hematita, Brazil and coupled with their low B contents of below detection limit to 2.2 ppm, these alexandrites can be unambiguously distinguished from all other sources (**Fig. 10.3**).

▶ Alexandrites from India stand out by their high V content of up to 0.15 wt% V_2O_3 and their low Sn (0.3–3.5 ppm), but they can also be distinguished from Russian samples by other element combinations such as the Ga to Ge or B to Ta ratios.

▶ Alexandrites from Sri Lanka are characterized by high B (7–125 ppm) and Ga (230–1333 ppm) values. These elements show a strong positive correlation throughout the data obtained from all sources.

▶ The ternary Ga-Ge-Cr diagram (**Fig. 10.4**) defines two separate population fields for alexandrites from Russia and Sri Lanka.

▶ Alexandrites from Lake Manyara, Tanzania differ from Russian specimens chiefly by their lower Sn values, with only slightly overlapping data. However, by additionally considering the B-Sn-Fe and the Ga-Ge-Cr ternary diagrams **Fig. 10.3 and 10.4**, a proper differentiation between the two source areas can be achieved.

Fig. 10.3 Ternary diagram showing relative percentages of B, Fe and Sn; components are weighted differently and source fields are defined by the outline of individual plotting points. The fields of alexandrites from Hematita, Brazil, India and Lake Manyara, Tanzania are distinctly separated from the field of Russian samples due to different B and Sn concentrations. The source field for the Sri Lankan alexandrites overlaps with that of Russian samples and other elements have to be considered for a clear separation from these sources.
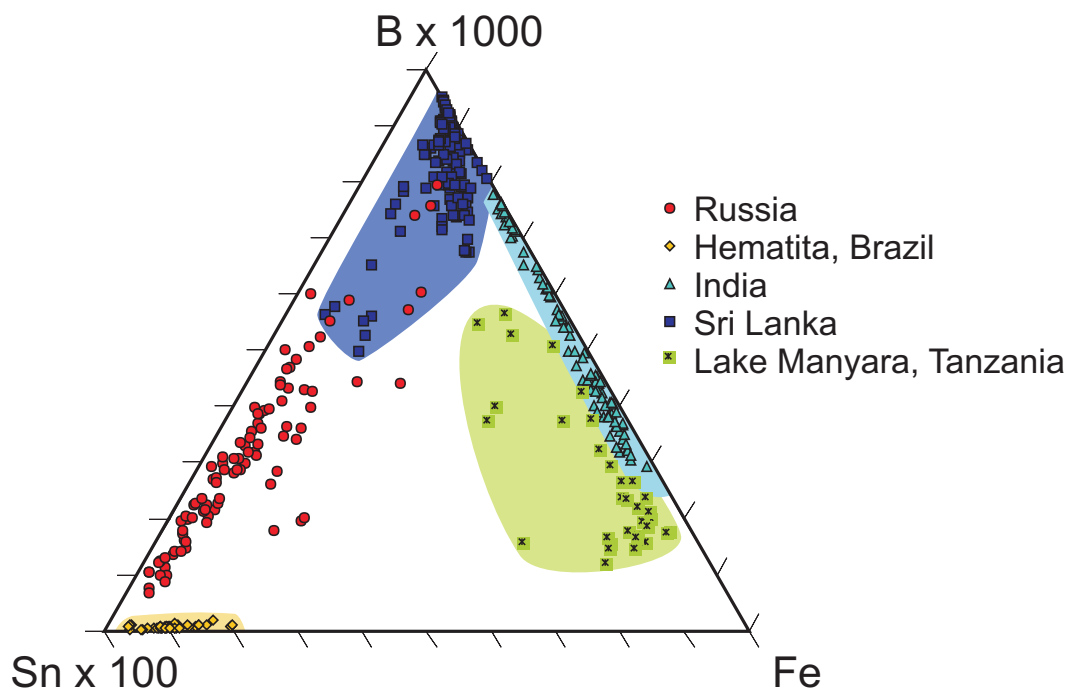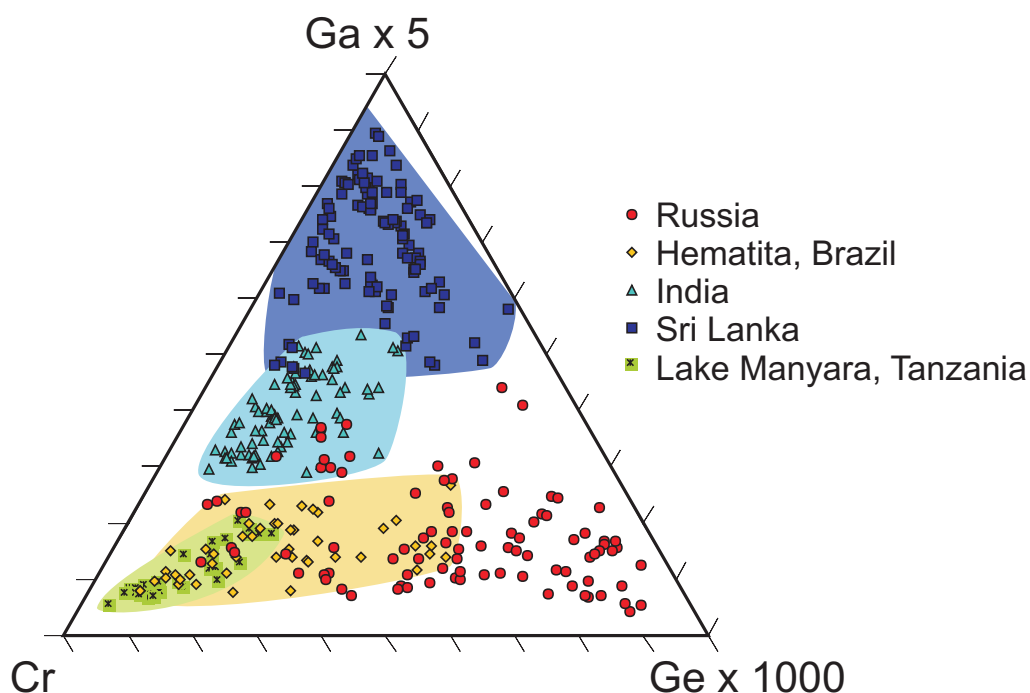
Figure 10.4 Ternary diagram showing relative percentages of Ga, Ge and Cr; components are weighted different-ly and source fields are defined by the outline of individual plotting points. Alexandrites from Sri Lanka show typi-cally high Ga concentrations and have a distinctive plot when Ge is also considered. Data from other sources over-lap with Russian samples to some extent.

It should be emphasised that only a few diagrams are giv-en here as examples and numerous other ternary dia-grams with additional elements and sources are applied for the origin determination of alexandrite as a routine laboratory service.

In summary, it was found that Russian alexandrites from Tokovaya mines in the Ural Mountains can be dis-tinguished from other sources by their trace element con-tents, especially by a combination of various ternary plots of selected trace elements. In addition to V, Cr and Fe as the main chromophore elements, B, Ga, Ge, Sn and Ta were shown to be the most relevant trace elements. As some of these elements such as B, Ge and Ta cannot be measured by energy dispersive X-ray fluorescence spectrometry in the small concentrations required, LA-ICP-MS is considered as a new standard analytical method for origin determination of alexandrites.

Appendix

Tables 1–7

Table 1: The most important emerald mines of the Tokovaya area, Urals, Russia (Izumrudnye Kopi)

No. on Map Fig. 2.4	Historical mine name	Discovered before 1850	Mine name in communist time (after 1927)[1]	In production after 1945[2]
1	Aulsky	no	Aulsky	yes
2	Mariinsky	yes	Malysheva	yes
3			Starkovsky	no
4	Starsky with Troitsky pit	yes	Pervomaisky	no
5	Makaryevsky	no	Artema	no
6	Tokovsky, changed to Lyublinsky in 1899 by "New Emeralds Company"	yes	Krupskoy	no
7	Sretensky (Stretensky)	yes	Sverdlovsky	yes[3]
8,9,10			less important pits or veins	no
11			Cheremshansky	yes
12	Chitny (Khitny)	yes	Krasnoarmeisky	yes
13	Krasnobolotsky[4]	yes	Krasnobolotsky	no
14	Ostrovnoye	yes	Ostrovnoye	no

[1] in recent publications, the historical names are reused again (see Zhernakov, 2009)
[2] after Laskovenkov and Zhernakov (1995), Semyonov and Timofeev (2005)
[3] reopened from 1995 to 1996
[4] also named Sarevtinsky mine in the first years (Grewingk, 1854)

Table 2: Morphological properties of Russian alexandrites

Crystal class 2/m 2/m 2/m = D2h, single and repeated twinning on (031) and (0$\bar{3}$1)

Crystal form	Designation	Miller indices hkl*
Pinacoid	a	100
Pinacoid	b	010
Prism	i	011
Prism	m	110
Prism	s	120
Dipyramid	o	111
Dipyramid	n	121
Dipyramid	w	122

*Based on a morphological cell with a 4.42, b 9.39, c 5.47

Characteristic angles frequently observed in Russian alexandrites, especially in trillings

Faces	Interfacial angles (°)	Angles formed by two faces (°)
o o' (adjacent)	40.21	139.79
o o' (diagonal)	107.66	72.34
o n	16.10	163.90
w w' (adjacent)	52.74	127.26
i i' (adjacent)	60.44	119.56
i b	59.78	120.22
View perpendicular to a twin plane		
a i	90	90
a o	43.08	136.92
i o	46.92	133.08
o o' (opposite)	93.84	86.16
o w	18.79	161.21
i w	28.13	151.87
w w' (opposite)	56.26	123.74
View parallel to the c-axis		
a b	90	90
a m	25.21	154.79
a s	43.27	136.73
b s	46.72	133.28
b m	64.79	115.21
m s	18.06	161.94

Habit of cyclic twins (trillings)

Habit	Dominant form	Subordinate forms	Accessory forms
Dipyramidal (type 1)	o	a	i, b, n, s
Dipyramidal (type 2)	o	a, b	i, n, s, m
Dipyramidal (type 3)	o	a, b, i	n, s, w
Tabular	a	i, o	b
Equidimensional	i, o	a	b
Columnar	i	a	o, b

Table 3: Characteristic angles observed in alexandrites from Sri Lanka for faces of the zone [001]

Faces*	Interfacial angles (°)	Angles formed by two faces (°)
ar	54.70	125.30
br	35.30	144.70
rr (over a)	109.31	70.61
rr (over b)	70.61	109.31

*Miller indices hkl: pinacoid a (100); pinacoid b (010); prism r (130)

Table 4: Colour, pleochroism and colorimetric parameters of a Czochralski-grown synthetic alexandrite[1]

Colour and pleochroism					
Direction of view	Light source	Colour to the unaided eye	Pleochroism X	Y	Z
View ∥ a-axis	daylight D_{65}	intense green	–	yellow green	blue green
	incandescent light A	bluish grey	–	yellow orange	blue green
View ∥ b-axis	daylight D_{65}	greenish blue	violet purple	–	blue green
	incandescent light A	intense purple	red purple	–	blue green
View ∥ c-axis	daylight D_{65}	light green	violet purple	yellow green	–
	incandescent light A	light greyish purple	red purple	yellow orange	–

Colorimetric parameters					
Direction of view	Light source	Chroma C^*_{ab}	Hue angle h_{ab}	Hue angle difference Δh_{ab} [2]	Colour difference ΔE^*_{ab} [3]
View ∥ a-axis	daylight D_{65}	26.38	174.8	91.1	28.39
	incandescent light A	9.76	265.8		
View ∥ b-axis	daylight D_{65}	13.18	229.5	79.9	26.03
	incandescent light A	24.83	309.4		
View ∥ c-axis	daylight D_{65}	13.36	185.7	129.8	25.88
	incandescent light A	15.17	315.4		

[1]   Orientation: a 4.42, b 9.33, c 5.47; X ∥ a, Y ∥ b, Z ∥ c
      lengths of the edges of the cube between 9.0 and 9.2 mm
[2]   between daylight and incandescent light
[3]   between daylight and incandescent light in the three dimensional CIELAB colour space

Table 5: Colorimetric parameters of alexandrites and chrysoberyls from Urals, Russia

	Group A	Group B	Group C[1]	Group D	Group E
Number of samples	5	11	3	7	3
Colour in daylight	Yellow green to yellowish green	Green to bluish green	Yellow to greenish yellow	Yellow green to yellowish green	Yellowish green to green
Colour in incandescent light	Purplish red to orange	Violet to reddish purple	Orange to yellow orange	Yellow to yellow green	Bluish grey or yellowish grey
C^*_{ab} for daylight D_{65}	10.24–19.54	2.43–13.18	11.56–15.27	11.18–18.43	8.90–11.31
h_{ab} (°) for daylight D_{65}	120.9–143.7	150.8–181.9	88.1–97.4	127.0–147.3	151.7–165.31
C^*_{ab} for incandescent light A	3.32–11.84	2.78–12.54	13.16–16.37	2.97–5.38	0.59–2.02
h_{ab} (°) for incandescent light A	11.9–60.2	299.8–351.7	51.4–70.08	85.0–126.7	74.5 or 248.1 or 257.4
Δh_{ab} (°)	71.4–126.4	123.0–178.4	27.4–42.9	15.6–55.7	77.2–101.2
ΔE^*_{ab}	11.27–19.51	9.70–21.05	6.93–11.64	7.63–15.4	8.92–11.22

[1] cat's-eyes cut as cabochons

C^*_{ab} = chroma; h_{ab} = hue angle
Δh_{ab} = hue angle difference between daylight and incandescent light
ΔE^*_{ab} = colour difference between daylight and incandescent light in the three-dimensional CIELAB colour space

Table 6: Operating parameters for Laser ablation and ICP-MS

Laser	CETAC LSX-213 Nd:YAG
Wavelength	213 nm
Repetition rate	10 Hz
Spot size	100 mm
Ablation mode	single-spot
ICP-MS	Perkin Elmer ELAN DRC-e
RF power	1400 W
Carrier gas flow	1 l/min (He)
Nebulizer gas flow	0.68 - 0.76 l/min (Ar)
Auxiliary gas flow	0.60 - 0.65 l/min (Ar)
Plasma gas flow	14 l/min (Ar)
Lense setting	Auto lens on

Table 7: Ranges of trace element and ultra-trace element contents of alexandrites and "green chrysoberyls" obtained by LA-ICP-MS.

	Ural, Russia alexandrite	Ural, Russia green chrysoberyl	Hematita, Brazil	India	Sri Lanka	Lake Manyara, Tanzania
[wt%]						
V_2O_3	0.002–0.031	0.006–0.030	0.010–0.021	0.059–0.149	0.002–0.073	0.001–0.025
Cr_2O_3	0.04–0.80	0.03–0.33	0.05–0.55	0.05–0.23	0.02–0.41	0.24–1.16
Fe_2O_3	0.23–2.01	0.28–0.84	0.71–1.39	0.22–0.74	0.52–1.29	0.50–1.13
[ppm]						
B	4.3–49	5.5–46	bdl–2.2	1.3–12	7–125	bdl–10
Ga	86–393	153–413	56–131	136–220	230–1333	64–181
Ge	0.7–17	0.7–8.7	bdl–1.4	bdl–0.78	bdl–2.6	bdl–1.5
Sn	22–1530	40–1437	274–2294	0.3–3.5	1.22–461	2.3–123
Ta	0.01–1364	0.3–1361	bdl–0.11	bdl–0.02	bdl–78	0.01–3.3

bdl = below the detection limit

Transcription of names

The English transcriptions of the original names of authors and other important persons have been used in this text in place of those used by 19th century Russian or German authors who published in Russian or German. In the reference list, the authors' names are cited as published in the original document. To avoid any confusion, a short list of the most frequently used names is given below. Less commonly used names are given in brackets.

English	German
Empress Alexandra Feodorovna	Zarin Alexandra Feodorowna
Fersman	Fersmann
Prince Kochubei	Fürst Kotschubey
Kokovin	Kokowin
Koksharov	von Kokscharow
Leskov	Leskow (Ljeßkow)
Tsar (Czar) Nicolas I (Nicholas, Nicolai)	Zar Nikolaus I
Nordenskiöld (Nordenskjold, Nordenskiold)	von Nordenskiöld (Nordenskjöld)
Count Perovskii	Graf Perowsky (Peroffsky)*
Prince Romanovskii, Duke of Leuchtenberg	Fürst Romanowsky, Herzog von Leuchtenberg
Russian Imperial Mineralogical Society	Russisch-Kaiserliche Gesellschaft für die Gesammte Mineralogie
Saint Petersburg	St.-Petersburg
Tokovaya	Tokowaya
Tsarevich Alexander Nikolaevich	Zarewitsch Alexander Nikolaewitsch
Veits	Weitz
Wörth (Vert)	von Wörth

*   the signature in his handwritten letters in French and German is L. Peroffsky

Timetable

Events relating to the discovery and naming of phenakite and alexandrite and the history of exceptional emerald and alexandrite specimens (1829–1913):

1829: Count Perovskii becomes Vice-President of the Appanage Department (Department Udelov) of the Russian Empire under Tsar Nicolas I.

1830: Kozhevnikov discovers emeralds in the roots of a fallen tree in the Tokovaya area.

January 1831: Start of emerald exploration under the guidance of Kokovin.

1831: Discovery of the **Kochubei emerald** and the **Leuchtenberg emerald druse**.

1831/1832: First notes about emeralds from the Urals including the **Kochubei emerald** and the **Leuchtenberg emerald druse**.

Fall 1832–Winter 1832/1833: First samples of phenakite were submitted by Perovskii to Nordenskiöld.

February 1833: Nordenskiöld reports on the properties of phenakite to Berzelius.

1833/1834: Discovery of Mariinsky deposit (Malysheva Mine in the 20th century).

1833/1834: Nordenskiöld describes phenakite as a new mineral from the Uralian emerald mines using the samples submitted by Perovskii.

Fall 1833: Discovery of the first alexandrites; samples are given by Kokovin to Perovskii and submitted to von Wörth for examination.

January 1834: Two small fragments of alexandrite are submitted by Perovskii to Nordenskiöld.

April 1834: Tsarevich Alexander Nikolaevich becomes of age.

April/May 1834: Additional alexandrite crystals are obtained by Perovskii from Kokovin and submitted to von Wörth and Nordenskiöld for examination.

June 1834: Report from Kokovin to Prince Gagarin in which he mentions the first colour-change alexandrite crystals and faceted gemstones.

August/October 1834: Nordenskiöld reports the properties of alexandrite as colour-change cymophane to Berzelius.

December 1834: Nordenskiöld sends one alexandrite crystal described as colour-change cymophane to Brewster for additional study.

February 1835: Note by Brewster on alexandrite describing it as colour-change cymophane.

June 1835: Inspection of Kokovin's office and private apartment was conducted by Yaroshevitskii from the Appanage Department resulting in the discovery of **Kokovin's emerald**, its transport to Saint Petersburg and the disappearance of this stone of exceptional quality.

December 1835: Kokovin is accused of misusing his position and of stealing emeralds and imprisoned; Veits becomes his successor.

1837: Tsarevich Alexander Nikolaevich visits the Urals and Ekaterinburg.

1838: Discovery of Krasnobolotsky deposit.

1839/1840: Discovery of large alexandrite crystals and crystals groups including **Kochubei's druse** in the Krasnobolotsky mining area.

1839: Rose describes perovskite as a new mineral from the Urals.

1839: Rose publishes a morphological description of alexandrite trillings.

1839: Maximilian, Duke of Leuchtenberg, marries Grand Duchess Maria Nikolayevna, the daughter of Tsar Nicolas I and sister of the future Tsar Alexander II.

1840: Death of Kokovin.

January 1840/June 1841: Berzelius reports on the analytical results of Uralian chrysoberyl to Nordenskiöld.

1841: Perovskii becomes Minister of the Interior.

1842: Awdejew publishes the first quantitative analysis of chromium and iron in Uralian chrysoberyl.

1842: Description and naming of alexandrite, including drawings by von Wörth in a contribution attributed later to Lenz, Rose, Veits and Nordenskiöld in the 25th year anniversary volume of the Russian Imperial Mineralogical Society edited by von Pott. In the same volume is a short description of the **Kochubei emerald** and the **Leuchtenberg emerald druse** as samples from the Imperial Cabinet.

1846/1847: Nordenskiöld describes diphanite as a new mineral from the Uralian emerald mines using samples submitted by Perovskii.

Circa 1847/1848: The **Leuchtenberg emerald druse**, a birthday present from Tsar Nicolas to his son-in-law, Maximilian, Duke of Leuchtenberg, is transported to the Principality of Eichstätt, Bavaria.

1849: Nordenskiöld visits the Urals for the first time.

1852: Perovskii becomes Minister of the Appanages and President of the Imperial Cabinet.

1852: Maximilian, Duke of Leuchtenberg dies in Saint Petersburg; subsequently his mineral collection including the **Leuchtenberg emerald druse** is transferred from Eichstätt to Munich, Bavaria.

1853: In his chapter on emeralds in Volume 1 of his "Materials of Russian Mineralogy" Koksharov briefly mentions exceptional samples that could be the **Kochubei emerald** and the **Leuchtenberg emerald druse**.

Summer/Fall 1853: Inspection of the emerald mines by C. Grewingk upon instruction of Perovskii.

1854: Grewingk publishes his report that includes a geological map of the Tokovaya area.

1855: Death of Tsar Nicolas I; the Tsarevich Alexander Nikolaevich becomes Tsar Alexander II.

1856: Death of Franz von Wörth.

1856: Death of Count Perovskii; his mineral collection is bought by Prince Kochubei.

1862: In the chapter on alexandrite in Volume 4 of his "Materials of Russian Mineralogy" and in a separate monograph, Koksharov describes a large alexandrite crystal group later named **Kochubei's druse**.

1865: The Koksharov collection is purchased by the British Museum.

1866: Death of Nils von Nordenskiöld.

1877: Pylyaev mentions in a gemmological textbook that it was Nordenskiöld who discovered alexandrite in the Urals.

1881: Assassination of Tsar Alexander II in Saint Petersburg.

1884: Leskov writes his novel "The Alexandrite", in which it is mentioned that Nordenskiöld discovered alexandrite in the Urals.

1891: Death of Nicolas, Duke of Leuchtenberg; in 1893, his widow donates his collection to the Mining Institute.

1892: Death of Nicolai von Koksharov.

1892: Death of Prince Petr Kochubei; his collection is kept at his country estate.

Post 1905: The Kochubei collection is transported to Kiev and later to Vienna by his son.

1911: Fersman and Vernadsky inspect the Kochubei collection in Vienna.

1913: Return of the Kochubei collection to Saint Petersburg; this includes the **Kochubei emerald** and **Kochubei's druse**, the largest alexandrite crystal group ever found in Russia.

References[1]

Abduriyim, A., and Kitawaki, H., 2006. Determination of the origin of blue sapphire using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). Journal of Gemmology, **30** (1/2), 23-36

Abduriyim, A., Kitawaki, H., Furuya, M., and Schwarz, D., 2006. Paraiba-type copper-bearing tourmaline from Brazil, Nigeria, and Mozambique: Chemical fingerprinting by LA-ICP-MS. Gems & Gemology, **42** (1), 4-21

Abduriyim, A., and Kobayashi, T., 2008. Properties of andesine from Tibet and Inner Mongolia. Gems & Gemology, **44** (4), 369-379

Alferova, M.S., and Boyd, W.F., 2007. Urals fieldtrip. The emerald mines & the demantoid mine. Guidebook prepared in conjunction with 30th International Gemmological Conference, 12 pp.

Alexandra Feodorova (Charlotte of Prussia). Available at http://en.wikipedia.org/wiki/Alexandra_Feodorovna_(Charlotte_of_Prussia)

Amburger, E., 1966. Geschichte der Behördenorganisation Russlands von Peter dem Großen bis 1917. Leiden, Brill Verlag, pp. 106-107, pp. 489-491

Arppe, A.E., 1867. Minnes-tal öfver Nils Gustaf Nordenskiöld. Acta Societas Scientiarum Fennicæ, **8** (2), 35 pp.

Avdonin, V.N., and Polenov, Yu.A., 2002. Essays on the Urals minerals. Ekaterinburg, UGGGA, 248 pp. (in Russian)

Von Awdejew, 1842. Ueber das Beryllium und dessen Verbindungen. Annalen der Physik und Chemie, **56**, 101-124

Bauer, M., 1896. Edelsteinkunde. Leipzig, Chr. Herm. Tauchnitz, pp. 345-346

Bauer, M., 1904. Precious stones. London, Charles Griffin & Company Ltd., Reprint: New York, Dover Publications Inc., 1968, Volume II, pp. 304-305

Berzelius, J.J., 1828. Die Anwendung des Löthrohrs in der Chemie und Mineralogie. 2nd Edition. Nürnberg, Joh. Leonhard Schrag, 273 pp.

Berzelius, J., 1836. Tetraphyllin. Jahresbericht über die Fortschritte der physischen Wissenschaften. Band **15**, Tübingen, Heinrich Laupp, pp. 212-213

Berzelius, J., 1837. Cymophan. Jahresbericht über die Fortschritte der physischen Wissenschaften. Band **16**, Tübingen, Heinrich Laupp, p. 177

Berzelius, J., 1848. Diaphanit. Jahres-Bericht über die Fortschritte der Chemie und Mineralogie, Band **27**, Tübingen, Laupp'sche Buchhandlung, p. 234

Bessudnova, Z.A., 2006. Nickolai Ivanovich Kokcharov, a founder of Russian mineralogy. Mineralogical Almanac, **10**, 34-45

Blum, J., 1971. Lord and peasant in Russia. Princeton, NJ, Princeton University Press, 656 pp.

Brewster, D., 1835. Notice of the optical properties of a new mineral supposed to be a variety of cymophane. The London and Edinburgh Philosophical Magazine and Journal of Science, **6**, 133-134

British Museum, 1904. The history of the collections contained in the Natural History Department of the British Museum. London, The Trustees of the British Museum, p. 373

Burlakov, J.V., Polenkov, J.A., Gernakov, V.J., and Samsonov, A.V., 1997. Tokowaja – Malyshevo: Die Smaragdgruben des Urals. Lapis, **22** (7/8), 44-55

Bukanov, V.V., 2006. Russian gemstones encyclopedia. Sankt Petersburg, Granit, s.r.o., 472 pp.

Bukin, G.V., Eliseev, A.V., Matrosov, V.N., Solntsev, V.P., Kharchenko, E.I., and Tsvetkov, E.G., 1980. The growth and examination of optical properties of gem alexandrite. In: Sidorenko, A.V. et al. (Eds.) Inhomogeneity of minerals and crystal growth. Proceedings of the XI General Meeting of IMA, Novosibirsk 1978, published Moscow 1980, pp. 317-328 (in Russian)

Cathrein, A., 1882. Ueber Alexandrit von der Tokowaia. Zeitschrift für Krystallographie und Mineralogie, **6**, 257-262

Chadwick, K.M., and Laurs, B., 2008. Yellow danburite from Tanzania. Gems & Gemology, **44** (2), 169-171

CIE Commission Internationale de l'Éclairage, 1986. Colorimetry. 2nd Edition, Publication CIE No. 15.2 (1986). Vienna, Austria, 74 pp.

CIE Commission Internationale de l'Éclairage, 2004. Technical Report. Colorimetry. 3rd Edition, CIE 15: 2004. Vienna, Austria, 72 pp.

---

[1] For the transcription of names from Russian and German original literature see Transcription of names, page 131.

Competent person's report on the Malyshev emerald mine, Sverdlovsk oblast, Russian Federation, 2007. Available at http://www.tsaremerald.com/uploads/TsarCPR23507.pdf?bcsi_scan1BCF1BFBAB29F929=D6uLYPQ3Elamljolhr8eWYUAAAA2+7gk&bcsi_scan_filename=TsarCPR23507.pdf

Crowningshield, G.R., 1960. Developments and Highlights at the Gem Trade Lab in New York. Gems and Gemology, **10** (2), 62

Crowningshield, R., 1963. Alexandrite cat's-eye. Gems and Gemology, **11** (4), 104-105

Deev, P.N., 1911. Troitsky emerald mine. In: Fersman, A. (Ed.) Emerald mines in Ural. Materials for research of natural minerals of Russia, Vol. **44/46**, Petrograd 1923, pp. 27-60 (in Russian)

Devnina, N.N., Kulikova, N.A., and Popova, E.E., 1994. Mineralogical collection of the Mining Museum, St. Petersburg Mining Institute. World of Stones, **9** (3), 17-34

Diener, R., 2008. Maximilian Eugene Josephe Napoleon de Beauharnais, der 3. Herzog von Leuchtenberg, Fürst von Eichstätt. Historischer Verein Eichstätt, Sammelblatt, **100**, pp. 7-47

Diener, R., 2009. Die russischen Herzöge von Leuchtenberg in Stein an der Traun und in Seeon und ihre Vorgeschichte. Historischer Verein Eichstätt, Sammelblatt, **101**, 125 pp.

Duparc, L., and Sabot, R., 1911. Chrysobéryl de Tokowaïa. Bulletin de la Société Française de Minéralogie, **34**, 139-141

Von Eichwald, Ed., 1870. Staatsrath Dr. Nils von Nordenskiöld und Wirklicher-Staatsrath Dr. Alexander von Nordmann, nach ihrem Leben und Wirken. Zapiski Imperatorskago St.-Petersburgskago Mineralogiceskago Obscestva (Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft zu St. Petersburg), 2nd Ser., **5**, 169-277

Elder, A., Madsen, S., Brown, G., Herbel, C., Collins, C., Whelan, S., Wenz, C., Alderson, S., and Kronthal, L., 1997. Adhesives and consolidants in geological and paleontological conservation: a wall chart. SPNHC Leaflets, **1** (2), 4 pp.

Emlin, E.F., 1996. The gem belt of the Urals: an interminable adventure. In: Urals! A special issue. World of Stones, **10**, 8-22

Farrell, E.F., and Newnham, R.E., 1965. Crystal-field spectra of chrysoberyl, alexandrite, peridot, and sinhalite. American Mineralogist, **50**, 1972-1981

Fersman, A.E., 1923. Archive materials on emerald mines. In: Fersman, A. (Ed.) Emerald mines in Ural. Materials for research of natural minerals of Russia, Vol. **44/46**, Petrograd 1923, pp. 5-6 (in Russian)

Fersman, A.E., 1925-1926. Russia's treasure of diamonds and precious stones. Part I (1925), Parts II, III, IV (1926), Moscow, The People's Commissariat of Finances

Fersmann, A., 1929. Smaragdgruben im Ural. In: Abhandlungen zur Praktischen Geologie und Bergwirtschaftslehre, Band **18**, Geochemische Migration der Elemente, Teil I, pp. 74-116

Fersman, A.E., 1946. Jewels of the Russian diamond fund. Gems and Gemology, **5** (8), 363-376

Fersman, A.E., 1947. Jewels of the Russian diamond fund. Part IV. Gems and Gemology, **5** (11), 467-470

Fersman, A.E., 1961. Emerald of Kakovin. In: Sketches of stone history. Vol. 2. Moskva, Akademii Nauk SSSR, pp. 75-77 (in Russian)

Fischer, W., 1954. Praktische Edelsteinkunde. 2nd Ed., Kettwig/Ruhr, Verlag Gustav Feller-Nottuln, pp. 94-96

Frischmann, L., 1867. Ueber die Zwillinge des Chrysoberylls. Sitzungsberichte der königl. bayer. Akademie der Wissenschaften zu München, **1867**, Band I, 429-434

Fryer, C.W. (Ed.), 1989. Gem trade lab notes. Phenomenal chrysoberyl. Gems & Gemology **25** (2), 102

G.I.A. Research Service, 1937. Star chrysoberyl. Gems and Gemology, **2** (8), 130

Goldschmidt, V., 1900. Zur Theorie der Zwillings- und Viellingsbildung, illustriert am Chrysoberyll. Zeitschrift für Krystallographie und Mineralogie, **33**, 468-476

Goldschmidt, V., and Preiswerk, H., 1900. Chrysoberyllzwilling von Ceylon. Zeitschrift für Krystallographie und Mineralogie, **33**, 455-467

Goldschmidt, V., 1913. Atlas der Krystallformen. Heidelberg, Carl Winters Universitätsbuchhandlung; Band II, Text: pp. 154-160, Tafeln: Tafeln 208-215

Golowin, I., 1845. Russland unter Nikolaus dem Ersten. Leipzig, Leopold Michelsen, pp. 248-249

Golynskaya, O.A., and Svirina, E.S., 1997. Pages from the history of mineralogy: Nils Gustaf Nordenskiöld (1792–1866). World of Stones, **12**, 28-33

Grewingk, C., 1854. Smaragd-Gruben des Ural. Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft, **1854**, 206-233

Grimm, A. Th., 1866. Alexandra Feodorowna, Kaiserin von Russland. Leipzig, Verlagsbuchhandlung von I.I. Weber, erster Band, 320 pp., zweiter Band, 396 pp.

Gromalova, N.A., Dorokhova, G.I., and Vigasina, M.F., 2006. Raman spectroscopy of inclusions in chrysoberyls from Ural emerald mines. Vestnik Moskovskogo Universiteta, Seriya 4: Geologiya, **2006** (2) 64-67 (in Russian)

Groth, P., 1891. Führer durch die Mineraliensammlung des Bayerischen Staates im Gebäude der Kgl. Akademie der Wissenschaften (Wilhelminum) in München. München, Verlag der K. b. Akademie der Wissenschaften, pp. 38-39

Gübelin Gem Lab Ltd., 2006. The roots of origin determination. Jewellery News Asia, No. **263**, 66-71

Guillong, M., and Günther, D., 2001. Quasi `non-destructive` laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) fingerprinting of sapphires. Spectrochimica Acta Part B, **56** (7), 1219-1231

Guillong, M., and Heinrich, C.A., 2007. Sensitivity enhancement in laser ablation ICP-MS using small amounts of hydrogen in the carrier gas. Journal of Analytical Atomic Spectrometry, **22** (12), 1488-1494

Haidinger, W., 1847. Ueber den Pleochroismus des Chrysoberylls. Berichte über die Mittheilungen von Freunden der Naturwissenschaften in Wien, **1847**, 440-447

Haidinger, W., 1849. Ueber den Pleochroismus des Chrysoberylls. Annalen der Physik und Chemie, **77**, 228-236

Halvorsen, A., and Molesworth, H., 2007. Discovery and naming of alexandrite. Gems & Jewellery, **16** (1) 8-10

Hassan, F., and El-Rakhawy, A., 1974. Chromium III centers in synthetic alexandrite. American Mineralogist, **59**, 159-165

Henn, U., 1985. Vergleichende chemische und optische Untersuchungen an Chrysoberyllen verschiedener Lagerstätten. Dissertation, Johannes Gutenberg-Universität Mainz, p. 95

Hey, M.H., 1955. An index of mineral species and varieties arranged chemically. 2nd Edition. London, The British Museum, pp. 403-404

Hunt, R.G.W., 2004. The reproduction of colour. Sixth Edition. Chichester, England; John Wiley & Sons, 679 pp.

Isogami, M., and Nakata, R., 1986. Chrysoberyl cat's-eye synthetic single crystal. US Patent 4,621,065, assigned to Kyocera Corporation, 4.11.1986

Kaluzhsky, G.A., 2001. Romanovs in the Urals. Available at http://www.koriphey.ru/samo/referat/index.php?_do=shw%7Creferat&referat%5Bid%5D=2&A%5Bpotok_id%5D=67&fa=245&referat3_pos=0

Kamenev, E.A., 1995. Alexander E. Fersman, a leader in the Sciences. 1883 – 1945. World of Stones, **10** (5-6), 58-60

Khroshevitskii, I.P., 1835. Results of the activity of Kokovin on the extraction of emeralds. In: Fersman, A. (Ed.) Emerald mines in Ural. Materials for research of natural minerals of Russia, Vol. **44/46**, Petrograd 1923, pp. 10-14 (in Russian)

Kievlenko, E.Ya., 2003. Geology of Gems. Chapter 3, Beryl. Littleton, Ocean Pictures Ltd., pp. 71-119

Klein, C., 1869. Über russische Chrysoberyll-Zwillinge (Alexandrit). Neues Jahrbuch für Mineralogie, Geologie und Palaeontologie, **1869**, 548-550

Klein, C., 1871. Chrysoberyll aus den Smaragdgruben an der Tokowaja. Neues Jahrbuch für Mineralogie, Geologie und Palaeontologie, **1871**, 479-485

Von Kobell, F., 1864. Geschichte der Mineralogie. Von 1650-1860. München, Cottasche Buchhandlung, p. 532

Koivula, J.I., and Kammerling, R.C. (Eds.), 1989. Gem news. Star chrysoberyl from Sri Lanka. Gems & Gemology, **25** (4), 255-256

Kokovin, Ya.V., 1831. Discovery of emerald in Ural. In: Fersman, A. (Ed.) Emerald mines in Ural. Materials for research of natural minerals of Russia, Vol. **44/46**, Petrograd 1923, pp. 7-10 (in Russian)

Von Kokscharow, N., 1853a. Materialien zur Mineralogie Russlands, Atlas. St. Petersburg, Carl Kray, Taf. 63, 64.

Von Kokscharow, N., 1853b. Materialien zur Mineralogie Russlands, Erster Band, St.-Petersburg, Carl Kray, pp. 180-184

Von Kokscharow, N., 1862a. Materialien zur Mineralogie Russlands, Vierter Band, St.-Petersburg, Alexander Jacobsen, pp. 56-88

Von Kokscharow, N., 1862b. Beschreibung des Alexandrits. Mémoires de l'Académie Impériale des Sciences de St.-Pétersbourg, VIIᴱ Série, Tome V, No. 2, 26 pp.

Von Kokscharow, N., 1865. Zwillinge des rhombischen Systems. In: Vorlesungen über Mineralogie. Erster Band. St.-Petersburg, Alexander Jacobsen, pp. 302-303

Kolomensky, V.D., and Fainstein, L.A., 1994. The Mining Museum in St. Petersburg. World of Stones, **9** (3), 6-16

Komonen, A., 1842. Leuchtenbergit. Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft, **1842**, 64-65

Königlich bayerische Akademie der Wissenschaften, 1847. Bericht von Professor von Kobell. Gelehrte Anzeigen, **25 (**256), 1017-1018

Kozlov, Yu.S., 2003. Alexandrite. Moscow, Nauka, 81 pp. (in Russian)

Kozlov, Yu.S., 2005. Alexandrite. Moscow, Nauka, 144 pp.

Kuhlmann, H., 1983. Emissionsspektralanalyse von natürlichen und synthetischen Rubinen, Sapphiren, Smaragden und Alexandriten. Zeitschrift der Deutschen Gemmologischen Gesellschaft, **32** (4), 179-195

Kuehni, R.G., 1997. Color: an introduction to practice and principles. New York, John Wiley & Sons, 186 pp.

Kulibin, S., 1892. Untitled [Nekrolog für Nikolai von Kokscharow]. Supplement added to: Von Kokscharow, N., 1891. Materialien zur Mineralogie Russlands, Elfter Band, St.-Petersburg, Alexander Jacobsen, pp. 131-137

Kumaratilake, W.L.D.R.A., 1997. Gems of Sri Lanka: a list of cat's-eyes and stars. Journal of Gemmology, **25** (7), 474-482.

Kunugi, M., 1984. Synthesis of chrysoberyl cat's eye. Japanese Patent Application Publication 59-152291 A, assigned to Seiko Epson Corp., 30.8.1984

Kupriyanova, I.I., 2002. Genesis of Malyshevsk beryl-emerald deposits (Central Urals, Russia). Geologiya Rudnykh Mestorozhdenii, **44** (4) 314-330 (in Russian)

Laitakari, A., 1934. Geologische Bibliographie Finnlands 1555-1933. Bulletin de la Commission Géologique de Finlande, No. 108, 224 pp.

Laskovenkov, A.F., and Zhernakov, V.I., 1995. An update on the Ural emerald mines. Gems & Gemolgy, **31** (2), 106-113

Von Lawrow, N., 1867. Erinnerung an Franz von Wörth dem früheren Sectretär der Kaiserlichen mineralogischen Gesellschaft. Zapiski Imperatorskago St.-Petersburgskago Mineralogiceskago Obscestva (Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft zu St. Petersburg), 2nd Ser., **2**, 305-311 (in Russian)

Leskov, N. S., 1884. The alexandrite (written 1884 in Russian). German Edition: Ljeßkow, N., 1923. Der Alexandrit, translated by J. von Guenther, München, Georg Müller, pp. 1-80

Liddicoat, R.T. Jr., 1976. One of the rarer. Gems & Gemology, **15** (6), 170

Liffa, A., 1902. Beiträge zur krystallographischen Kenntnis des Chrysoberylls von Ceylon. Zeitschrift für Krystallographie und Mineralogie, **36**, 606-616

Liu, Y., Shigley, J.E., Fritsch, E., and Hemphill, S., 1995. Relationship between the crystallographic orientation and the 'alexandrite effect' in synthetic alexandrite. Mineralogical Magazine, **59**, 111-114

Liu, Y., and Hurwit, K.N., 2008. The TrueGemColor system: a new computer color imaging system based on a uniform CIELAB color space for color grading of gemstones. Gemmologie. Zeitschrift der Deutschen Gemmologischen Gesellschaft, **57** (3-4), 133-142

Longerich, H.P., Jackson, S.E., and Günther, D., 1996. Laser ablation inductively coupled plasma mass spectrometric transient signal data acquisition and analyte concentration calculation. Journal of Analytical Atomic Spectrometry, **11** (9), 899-904

Lyckberg, P., 1993. Eine Reise zu den Smaragd-Vorkommen im Bereich von Tokovaja im Ural. Mineralien-Welt, **4** (3), 53-59

MacEvoy, B., 2005. Handprint: color vision. Available at http://handprint.com/LS/CVS/color.html (different chapters updated and revised at different times)

McClure, S.F, and Shen, A.H., 2008. Coated tanzanite. Gems & Gemology, **44** (2), 142-155

McLean, H., 1977. Nikolai Leskov. The man and his art. London & Cambridge, Harvard University Press, 780 pp.

Meiksina, Yu. L., and Evdokimov, M.D., 2003. Plagioclases in the Urals emerald mines. Zapiski Rossiiskogo Mineralogicheskogo Obshchestva, **132** (3), 130-138 (in Russian)

Meiksina, Yu. L., and Evdokimov, M.D., 2005. Physical-chemical conditions of the emerald mineralization forming by example of the Urals localities. Zapiski Rossiiskogo Mineralogicheskogo Obshchestva, **134** (2), 57-67 (in Russian)

Melczer, G., 1900. Ueber einige Mineralien, vorwiegend von Ceylon. Zeitschrift für Krystallographie und Mineralogie, **33**, 240-262

Moisseeva, M.L., 2003. Petr A. Kochubei and his mineral collection in A.E. Fersman mineralogical museum. Mineralogical Almanac, New Data on Minerals, **38**, 89-98

Morosov, A.V., 1913. Catalogue of my collection of Russian engraved lithographed portraits. Moskva, 1913, Vol. 3, p.843, plate 316a (in Russian)

Morris, R.C., and O'Dell, E.W., 1981. Multi-element pleochroic gemstones. US Patent 4,262,497, assigned to Allied Chemical Corporation, 21.4.1981

Nefedev, V.V., 1871. Concise catalogue of the mineralogical collection, Mining Institute Museum. Saint Petersburg, p. 165 (in Russian)

Nicolas, July 2nd 1839. Manifeste de Sa Majesté l'Empereur. In: Aegidi, L.K., and Klauhold, A., 1863. Das Staatsarchiv. Sammlung der officiellen Actenstücke zur Geschichte der Gegenwart. Vierter Band, Hamburg, Otto Meissner, p. 119

Niggli, P., 1927. Tabellen zur allgemeinen und speziellen Mineralogie. Berlin, Verlag von Gebrüder Borntraeger, p. 118

Nordensköld, N., 1833. Der Phenakit, ein neues Mineral. Annalen der Physik und Chemie, **28**, 420

Nordenskjöld, N., 1834. Beschreibung des Phenakits, eines neuen Minerals aus dem Ural. Annalen der Physik und Chemie, **31**, 57-62

Nordenskiöld, N., 1846. Beschreibung des Diphanits, eines neuen Minerals aus den Smaragdgruben des Urals unweit Katharinenburg. Journal für Praktische Chemie, **39**, 114-115

Nordenskiöld, N., 1847. Beschreibung des Diphanits, eines neuen Minerals aus den Smaragdgruben des Urals, unweit Katherinenburg. Annalen der Physik und Chemie, **70**, 554-556

Nordenskiold, N., 1857. Ueber Lasurstein und die mit demselben vorkommmenden Mineralien. Bulletin de la Société Impériale des naturalistes de Moscou, **30**, 213 – 226

Novgorodova, M.I., and Mokhova, N.A., 2005. Struve collection. Treasures of Fersman Mineralogical Museum, RAS. Moscow, Fersman Mineralogical Museum, 100 pp.

Novgorodova, M.I., and Leybov, M.B., 2008. For 125-anniversary of Alexander E. Fersman. Mineralogical Almanac, **13c**, 52-55

Oguri, H., and Hirota, M., 1985. Chrysoberyl single crystal showing iridescent effect and process for its preparation. European Patent Application Publication 0 148 946 A1, assigned to Sumitomo Cement Co. Ltd., 24.7.1985

Ohta, N., and Robertson, A.R., 2005. Colorimetry: fundamentals and applications. Chichester, John Wiley & Sons, 334 pp.

Ottemann, J., 1965. Gallium und Zinn in Alexandrit. Neues Jahrbuch für Mineralogie Monatshefte, **1965** (2), 31-42

Ottemann, J., Schmetzer, K., and Bank, H., 1978. Neue Daten zur Anreicherung des Elements Gallium in Alexandriten. Neues Jahrbuch für Mineralogie Monatshefte, **1978** (4), 172-175

Pierer's Universal-Lexikon der Vergangenheit und Gegenwart, 4. Aufl., Zwölfter Band, 1861. Altenburg, Verlagsbuchhandlung von H. A. Pierer, p. 840 (Perowsky)

Pinheiro, M.V.B., Basílio, M.S., Krambrock, K., Dantas, M.S.S., Paniago, R., Assunção, A.L., and Pedrosa-Soares, A.C., 2000. The cause of colour of the blue alexandrites from Malacacheta, Minas Gerais, Brazil. Journal of Gemmology, **27** (3), 161-170

Pfaffl, F., 1978. Die Edelsteinsammlung des Herzogs Maximilian von Leuchtenberg (1817-1852) in Eichstätt (Bayern). Beitrag zur Geschichte der Mineralogischen Staatssammlung München. Aufschluß, **29** (6), 175-191

Poggendorff, J.C. (Ed.), 1835. Farberscheinungen bei chromhaltigen Salzen. Annalen der Physik und Chemie, **35**, 383-384

Popov, M.P., Zhernakov, V.I., Zolotukhin, F.F., and Samsonov, A.V., 1998. Ural emerald mines. Ekaterinburg, UGGGA, 90 pp. (in Russian)

Von Pott, H.A.G. (Ed.), 1842a. Ehrenmitglieder der Gesellschaft. Geschichte und wissenschaftliche Beschäftigungen der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie von 1817 bis 1842. Schriften der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie, I. Band, I. Abtheilung, pp. 15-20

Von Pott, H.A.G. (Ed.), 1842b. Sibirischer Smaragd. Geschichte und wissenschaftliche Beschäftigungen der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie von 1817 bis 1842. Schriften der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie, I. Band, I. Abtheilung, pp. 55-60, pp. 126-129

Von Pott, H.A.G. (Ed.), 1842c. Ueber den ALEXANDRIT, oder Uralschen Chrysoberyll, dessen Dichroismus und über die ungewöhnliche Grösse seiner Krystalle. Geschichte und wissenschaftliche Beschäftigungen der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie von 1817 bis 1842. Schriften der in St. Petersburg gestifteten Russisch-Kaiserlichen Gesellschaft für die gesammte Mineralogie, I. Band, I. Abtheilung, pp. 116-126

Powell, R.C., Xi, L., Gang, X., and Quarles, G.J., 1985. Spectroscopic properties of alexandrite crystals. Physical Review B, **32** (5), 2788-2797

"Protokoll der Sitzung am 26. Januar", 1863. Verhandlungen der Kaiserlichen Gesellschaft für die Gesammte Mineralogie zu St. Petersburg, **1863** (published 1864), p. 167

Pylyaev, M.I., 1877. Precious stones: their properties, localities and use. 1st Edition. St.-Petersburg, Academy of Science, pp. 43-45 (in Russian)

Pylyaev, M.I., 1888. Precious stones: their properties, localities and use. 2nd Edition. St.-Petersburg, Suvorin, pp. 76-79 (in Russian)

Pylyaev, M.I., 1990 (1888). Precious stones: their properties, localities and use. 2nd Edition. St.-Petersburg, Suvorin. Reprint: Moskva, Sovmestnoe Sovetsko-Avstrijskoe Predprijatie "Ch. G. S." 1990, pp. 76-79 (in Russian)

Rabadanov, M.Kh., and Dudka, A.P., 1998. On localization of impurity ions in alexandrite. Crystallography Reports, **43** (6), 991-994

Rager, H., Bakhshandeh-Khiri, A., and Schmetzer, K., 1998. Investigation of the intracrystalline Cr^{3+} distribution in natural and synthetic alexandrites. Neues Jahrbuch für Mineralogie Monatshefte, **1998** (12), 545-557

Risåsen, G.T., 2006. The Norwegian crown regalia. Oslo, press publishing, 108 pp.

Richter, K., 1996. Computergrafik und Farbmetrik. Berlin und Offenbach, VDE-Verlag, 288 pp.

Roemer, F., 1862. Bericht über eine geologische Reise nach Russland im Sommer 1861. Zeitschrift der Deutschen geologischen Gesellschaft, **14**, 178-233

Rondeau, B., Fritsch, E., Peucat, J.-J., Nordrum, F.S., and Groat, L., 2008. Characterization of emeralds from a historical deposit: Byrud (Eidsvoll), Norway. Gems & Gemology, **44** (2), 108-122

Rose, G., 1839a. Der Perowskit, eine neue Mineralgattung. Annalen der Physik und Chemie, **48**, 558-561

Rose, G., 1839b. Ueber den Chrysoberyll vom Ural. Annalen der Physik und Chemie, **48**, 570-573

Rose, G., 1842. Ueber den Chrysoberyll vom Ural. In: Reise nach dem Ural, dem Altai und dem Kaspischen Meere. Zweiter Band. Berlin, Verlag der Sanderschen Buchhandlung, pp. 379-382

Royal Family Imperial Style. Russain Court Dress. Available at http://www.tristarmedia.com/bestofrussia/style3.html

Sakharov, I., 1998. Subjects of the French Kings → Bavarian Dukes → members of the Russian Imperial House → citizens of Germany, France, Canada, USA: the Beauharnais over the last 200 years. Genealogica & Heraldica, Ottawa 1996, University of Ottawa Press 1998, pp. 249-253

Saminpanya, S., Manning, D.A.C, Droop, G.T.R., and Henderson C.M.B., 2003. Trace elements in Thai gem corundum. Journal of Gemmology, **28** (7), 399-415

Schmetzer, K., Bank, H., and Gübelin, E., 1980. The alexandrite effect in minerals: chrysoberyl, garnet, corundum, fluorite. Neues Jahrbuch für Mineralogie Abhandlungen, **138** (2), 147-164

Schmetzer, K., Bernhardt, H.-J., and Biehler, R., 1991. Emeralds from the Ural mountains, USSR. Gems & Gemology, **27** (2), 86-99

Schmetzer, K., Peretti, A., Medenbach, O., and Bernhardt, H.-J., 1996. Russian flux-grown synthetic alexandrite. Gems & Gemology, **32** (3), 186-202

Schmetzer, K., Bernhardt, H.-J., Bosshart, G., and Hainschwang, T., 2009. Colour-change garnets from Madagascar: variation of chemical, spectroscopic and colorimetric properties. Journal of Gemmology, **31** (5-8), 235-282

Schrauf, A., 1869. Handbuch der Edelsteinkunde. Wien, Carl Gerold's Sohn, pp. 127-136

Schrauf, A., 1877. Atlas der Krystall-Formen des Mineralreiches. Wien, Wilhelm Braumüller, Band I, 5. Lieferung, Taf. 45

Schwarz, D., Pardieu, V., Saul, J.M., Schmetzer, K., Laurs, B., Guiliani, G., Klemm, L., Malsy, A.-K., Erel, E., Hauzenberger, C., Du Toit, G., Fallick, A.E, and Ohnenstetter, D., 2008. Rubies and sapphires from Winza, central Tanzania. Gems & Gemology, **44** (4), 322-347

Semyonov, V.B., 2003. Kokovin. In: Timofeev, N.I., Ed., Ekaterinburg stone cutting and antique factory: 1805-1861. Ekaterinburg, IGEMMO "Lithica", pp. 714-719 (in Russian)

Semyonov, V.B., and Timofeev, N.I., 2005. Emerald years of peace. Stone of Russia. Ekaterinburg, Timofeev Foundation; IGEMMO "Lithica", 560 pp. (in Russian)

Semyonov, V.B., and Shakino, I.M., 1982. The tragedy of Yakov Kokovin. In: Gemstones of the Urals. Available at http://www.eunnet.net/lithica/ural/1982/chapter3/chap3_5.htm (in Russian)

Shindo, I., Sakauchi, H., and Takegawa, S., 1982. Preparation of single crystal of chrysoberyl shedding luster. Japanese Patent Application Publication 57-191297 A, assigned to Natl. Inst. for Res. in Inorg. Mater., 25.11.1982

Söderbaum, H.G., 1927. Brevväxling mellan Berzelius och Nils Nordenskiöld (1817–1847). Jac. Berzelius lettres, Vol. **11**, publées au nom de l'Académie Royale des Sciences de Suède, Uppsala, Almqvist a Wiksells Boktryckeri, 331 pp.

Sreznevskii, V.I., 1893. Story of life and activities of Petr Arkad'evich Kochubei. 1825–1892. Saint Petersburg, Vladimirskaya Parovaya Tipo-Lithographia, 24 pp. (in Russian)

Von Struve, H., 1832. Letter to the Editor. Jahrbuch für Mineralogie, Geognosie, Geologie und Petrefaktenkunde, **3**, 209

Svirina, E.S., 1994. Earl Perovsky (1792-1856) and his beryl collection in the Mining Museum. World of Stones, **9** (3), 35-38

Treasures hidden by the imperial family in Tobolsk. Available at http://www.alexanderpalace.org/palace/jewelslist.html

Twining, E.F., 1960. A history of the crown jewels of Europe. London, B.T. Batsford Ltd, p. 454, p. 531

Ustinov, V.I., and Chizhik, O.Ye., 1994. Sequential nature of the formation of emerald and alexandrite in micaite-type deposits. Geochemistry International, **31** (7), 115-118

Vandenabeele, P., Moens, L., Edwards, H., De Reu, M., and Van Hooydonk, G., 2000a. Identification and classification of natural organic binding media and varnishes by micro-Raman spectroscopy. 15th World Conference on Non-Destructive Testing, Proceedings, 4 pp.

Vandenabeele, P., Wehling, B., Moens, L., Edwards, H., De Reu, M., and Van Hooydonk, G., 2000b. Analysis with micro-Raman spectroscopy of natural organic binding media and varnishes used in art. Analytica Chimica Acta, **407**, 261-274

Veits, I.I., 1842. Extraction of emeralds, chrysoberyl, phenacite and other minerals from Urals. In: Fersman, A. (Ed.) Emerald mines in Ural. Materials for research of natural minerals of Russia, Vol. **44/46**, Petrograd 1923, pp. 14-22 (in Russian)

Venturini, C., 1836. Chronik des neunzehnten Jahrhunderts. Neue Folge, Neunter Band, das Jahr 1834 enthaltend. – Pragmatische Geschichte unserer Zeit. Das Jahr 1834. Leipzig, J.C. Hinrichssche Buchhandlung, p. 503

Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft **1854**, Register-Heft aller bisher von der Mineralogischen Gesellschaft zu St. Petersburg herausgegebenen Zeitschriften, pp. 251-284, Alphabetisches Autoren- und Sach-Register, p. 261

Vice-President of Appanage Department [L.A. Perovskii], 1831. About finding of emeralds in Ural mountains. Gornyi Zhurnal (Mining Journal), Vol. **1831,** Part **2**, No. 4, 147-148 (in Russian)

Vlasov, K.A., and Kutukova, E.J., 1960. Izumrudnye Kopi (emerald mines). Izdanie Akademii Nauk SSSR, Moscow, p. 45 (in Russian)

Walling, J.C., Jenssen, H.P., Morris, R.C., O'Dell, E.W., and Peterson, O.G., 1979. Tunable-laser performance in $BeAl_2O_4$: Cr^{3+}. Optics Letters, **4** (6), 182-183

Weber, S.-U., Grodzicki, M., Lottermoser, W., Redhammer, G.J., Tippelt, G., Ponahlo, J., and Amthauer, G., 2007. ^{57}Fe Mössbauer spectroscopy, X-ray single crystal diffractometry, and electronic structure calculations on natural alexandrite. Physics and Chemistry of Minerals, **34** (7), 507-515

Weinberg, D., 2007. Alexandrite Gemstone Encyclopedia & Jewelry Collector Guide. Alexandrite Tsarstone Collectors Guide; see especially: Chapter 1. Insidious Siberian (the prophetic Russian stone) and Chapter 2. Diaphanite or Alexandrite? Available at http://www.alexandrite.net/

Wyszecki, G., and Stiles, W.S.,1982. Color Science: concepts and methods, quantitative data and formulae. 2nd Edition. New York, John Wiley & Sons, 923 pp.

Yaroshevitskii, I.P., 1835 see Khroshevitskii, I.P.

Yeom, T.H., and Choh, S.H., 2001. Cr^{3+}(I) and Cr^{3+}(II) centers in alexandrite single crystal. Journal of Applied Physics, **90** (12), 5946-5950

Zhernakov, V.I., 2009. Ural emerald mines (Izumrudnye Kopi): Notes on mineralogy. Mineralogical Almanac **14** (2), 1-128

Zolotukhin, F.F., and Laskovenkov, A.F., 1991. Maryinsky emerald deposit. Unpublished manuscript, 37 pp.

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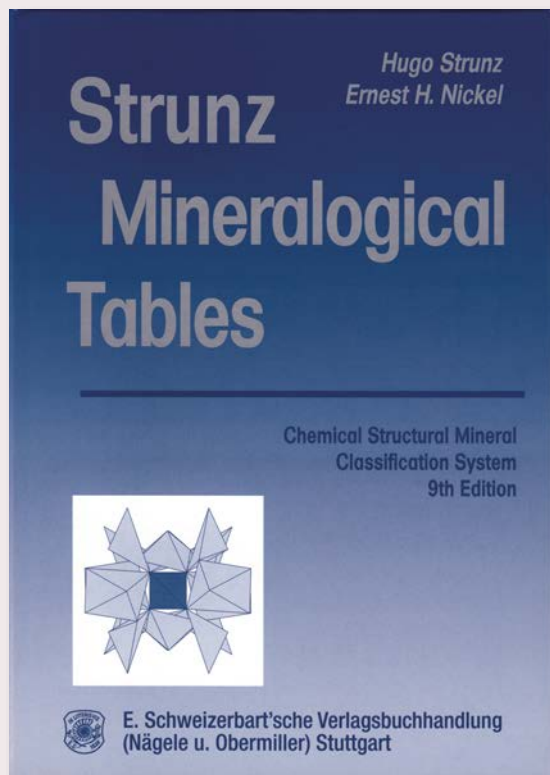
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Prof.-Schlossmacher-Strasse 1
D-55743 Idar-Oberstein, Germany

phone: +49-6781-5084-0 · fax: +49-6781-5084-19
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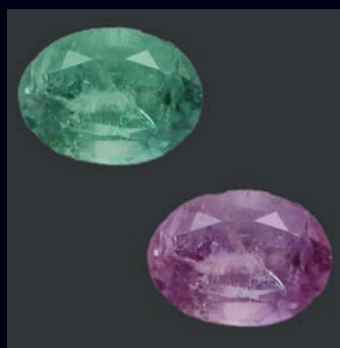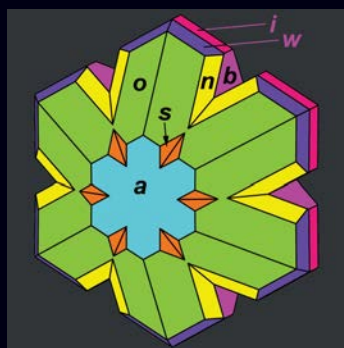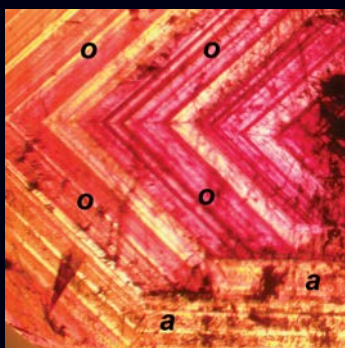
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Русскіе Александриты

Russian Alexandrites

Alexandrite, a variety of chrysoberyl, and one of the finest colour-change natural gemstones, may almost be called "the national gemstone of Russia". This great prestige is based on two facts: its noble name in honour of the Tsarevich Alexander Nikolaevich (the future Tsar Alexander II) and its dazzling colours, green in daylight and red in incandescent light, the military colours of Imperial Russia. Although quantities of facetable quality alexandrite are considerably less than those of emerald, alexandrite is counted among and compared to the "big four" of the gem business: diamond – ruby – sapphire – emerald.

In this book the authors present an historical overview of emerald mining in the Urals, the discovery of Russian alexandrites in the Uralian emerald mines, the naming and historical use of alexandrites and their appearance and display in mineralogical museums and the gem trade.

Morphology and twinning of rough alexandrite is described for single crystals, single contact twins and cyclic twins (trillings). Mineralogical and gemmological properties are thoroughly explained and numerous photo-micrographs of inclusions and growth patterns in faceted samples are presented.

Chatoyancy and asterism of alexandrite and chrysoberyl from Russia and Sri Lanka are also described. A further chapter deals with characteristic growth patterns of Russian, other natural and synthetic alexandrites. Colorimetric data of Russian alexandrites and green chrysoberyls are explained using the CIELAB colour space, and the distinction between these varieties is explained. A chapter on trace element chemistry and locality determination rounds off the book.

An extensive appendix containing lists of historical names, a time table and numerous references provides valuable information on Russian alexandrites for all researchers in the mineralogical and gemmological fields as well as for gemmological laboratories, jewellers and gem dealers.

Consequently, this book, illustrated with more than 200 colour figures and photographs, addresses mineralogists, gemmologists, historians, mineral and gem collectors as well as all members of the gem trade.