

Investigations on sapphires from an alkali basalt, South West Rwanda

M.S. Krzemnicki,¹ H.A. Hänni,² R. Guggenheim³ and D. Mathys³

1. Mineralogical Petrographical Institute, University Basel, Switzerland

2. SSEF Swiss Gemmological Institute, Basel, Switzerland

3. SEM-Laboratory, University Basel, Switzerland

Abstract

A new deposit of sapphires in the Cyangugu district of SW Rwanda has been investigated. The sapphires are believed to have originated from a specific alkali basalt lava flow, extruded during the Tertiary extensional regime along the East African Rift. They exhibit mainly a deep blue colour, often showing so-called silk (inclusions of hematite or rutile) or a slight milkiness possibly due to submicroscopic exsolution of these minerals. Greyish 'geuda'-type crystals are known to convert to a blue colour by heat treatment. Values for the refractive indices and specific gravity are given, as well as VIS-IR data. Studies of the inclusions reveal the presence of Ti and Fe oxides, silicates, spinel, zircon and a complex Th-REE phosphate as solid inclusions; the presence of CO₂ in fluid inclusions was determined by microthermometric methods. Studies of crystal surfaces by SEM show corrosion or abrasion features, both primary and secondary. The primary corrosion occurred during the transport of the deep-crustal sapphires to the surface; it can be attributed to the high-temperature magma. Secondary abrasion took place during the erosion and weathering of the basalt and the subsequent formation of alluvial sapphire deposits.

Keywords: sapphire, alkali basalt, inclusions, corrosion, scanning electron microscopy

Introduction

East-Central Africa is well known for rich gemstone deposits. Extensive sapphire mining has been described from the Umba river (Tanzania), Garba Tula and Turkana (Kenya) (Hughes, 1990; Themelis, 1989; Hänni, 1986; Kanis and Harding, 1990; Barot and Harding, 1994).

Rwanda, at present in the political focus because of the tragic civil war, was until now barely known for gemstone deposits. One of the authors (MSK) recently had the opportunity to investigate a new sapphire deposit in a basalt province in the Cyangugu district, SW Rwanda (Figure 1). This investigation was made possible by kind support of J.F. Damon (Twin Gems, Washington DC).

After a geological field trip of two months which included trenching and sampling in a region of approximately 200km², some areas of major interest for sapphire mining were established (Figure 2). Due to the rapid decomposition of rocks in a tropical humid climate, the main sapphire deposits are of alluvial type. They are exploited mostly by the local population using traditional methods (Figure 3). Twenty representative sapphire samples from the Cyangugu district were selected for the laboratory and investigated by various methods, including spectrophotometry

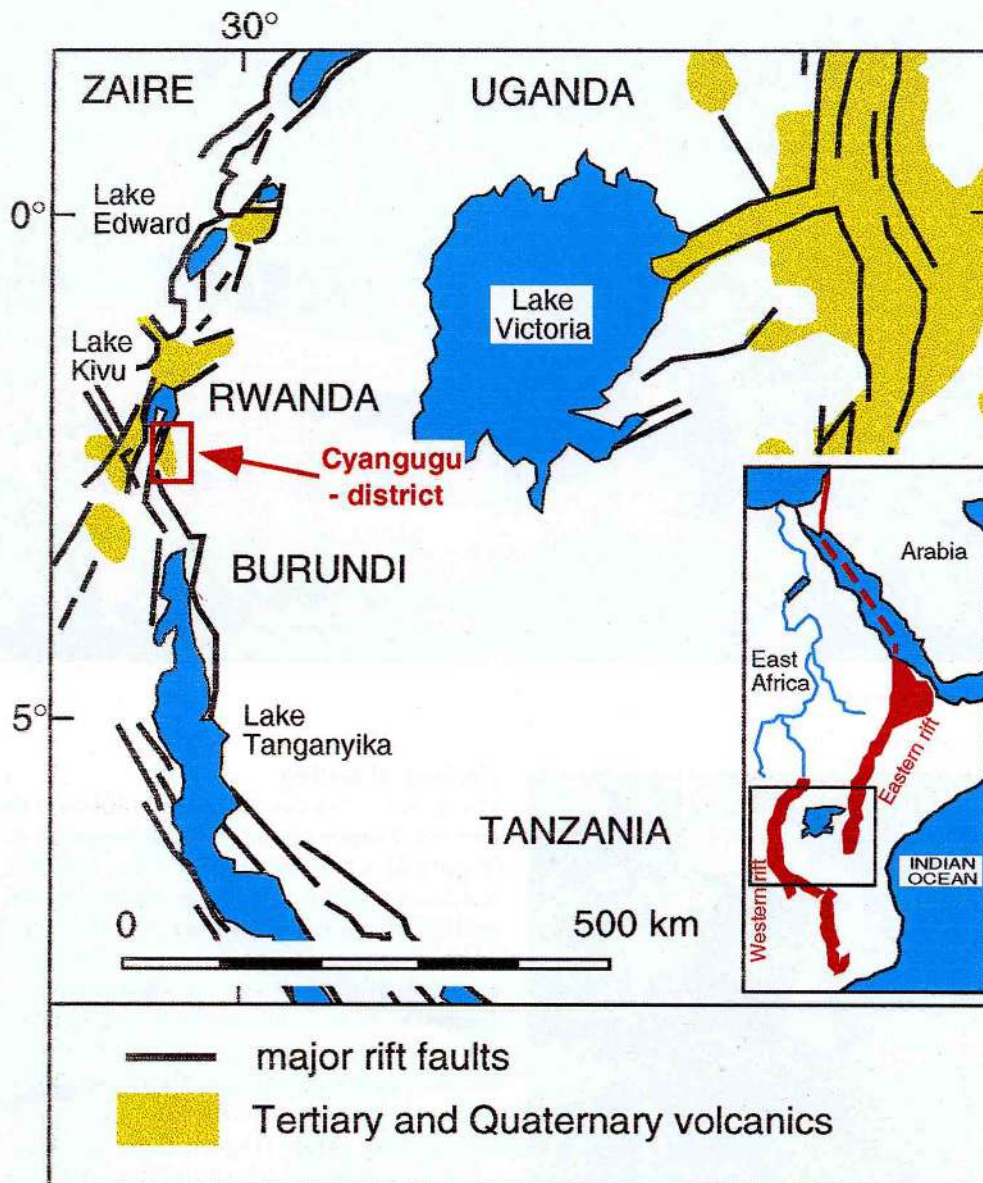


Fig. 1. Simplified geological map (after: Wilson, 1991).

(VIS-IR), SEM-EDX, ED-XFA, EMP-WDX, microthermometry and optical microscopy (OM) (Table I). During these analytical procedures information was gained about the trace elements responsible for colour, solid as well as fluid inclusions and surface fea-

tures of sapphire crystals. In particular, a specific surface feature, which resulted from a shielding effect of plagioclase on sapphire and which influenced the primary corrosion in the basalt in a very spectacular way was observed.



Fig. 2. Prospecting trench in an alluvial deposit in the Cyangugu district.

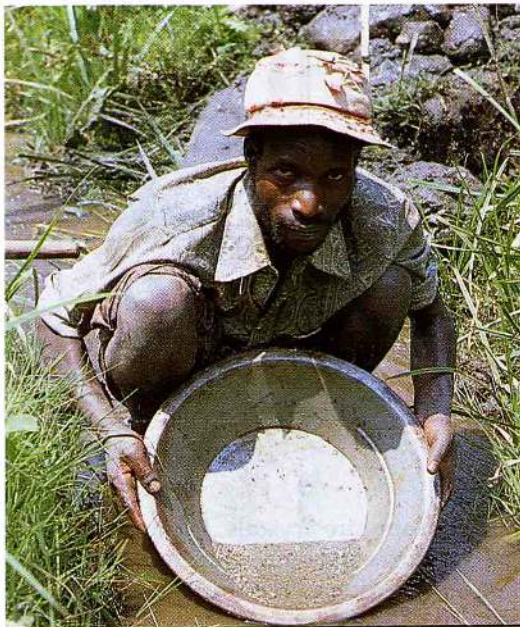


Fig. 3. Local resident, working the alluvial deposit by traditional methods.

Geological setting

The western border of Rwanda follows the western branch of the East African rift (Figure 4), a continental rift zone, which has been tectonically active for the last 45 million years, i.e. since the early Tertiary. It forms a part of the Afro-Arabian rift system, which extends some 6500 km from Turkey to Mozambique. As a result of the extensional tectonics along this rift, the Red Sea opened in the northern part, whereas in the south, rifting occurred to a much lesser extent (Figure 1).

The western branch of the East African Rift has developed in a rather episodic way, accompanied by intense extensional faulting of the Precambrian basement. The basement is characterized by continental sedimentary rocks, i.e. sandstones and arkoses lying on a metamorphic substratum of gneisses and amphibolites. Upwelling of asthenosphere (upper mantle) caused a regional domal uplift

Table I: Gemmological properties of sapphires from Cyangugu district, SW Rwanda

| | |
|---|---|
| Colour and visual appearance with unaided eye: | dark blue, transparent to semitransparent with microscopic and submicroscopic inclusions ('silk') |
| Refractive index: | n_o 1.770–1.771 n_e 1.761–1.762 |
| Birefringence: | Δ_n -0.009 |
| Specific gravity: | 3.998–4.005 |
| Dichroism: | greenish-blue and dark blue |
| Absorption spectrum: | absorption features at 375nm, 390nm, 450nm and a broad absorption band at 890nm |
| Reaction to long wave and short wave ultraviolet radiation: | no fluorescence |



Fig. 4. The Ruizi river in the western branch of the East African rift valley, SW Rwanda.

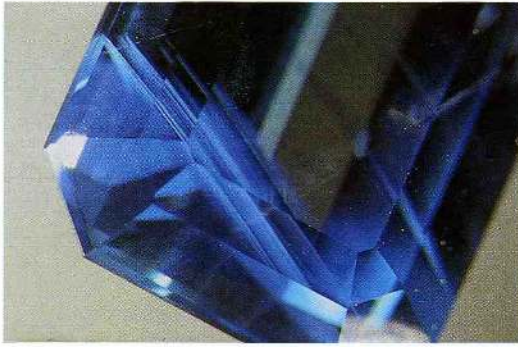


Fig. 5. Faceted sapphire from Cyangugu district, SW Rwanda.

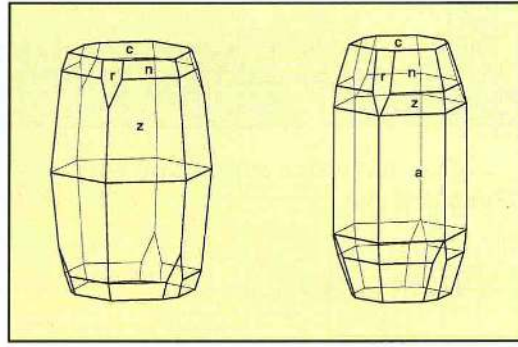


Fig. 7. Crystal habit of prismatic sapphires (after: Kiefert, 1987).

combined with intracontinental basaltic volcanism, which is typically dominated by alkali basalts (Cahen *et al.*, 1984; Wilson, 1991) (Figure 6).

The sapphire deposits in SW Rwanda are connected to this Tertiary-Quaternary volcanic activity. The sapphires have been brought to the surface by an alkali-basaltic magma, in which they were transported as xenoliths (alien crystals, separated in the upper mantle or deep crust from their original melt or rock). Alkali basaltic rocks as parent rocks of corundum are encountered in many places worldwide, and economically important deposits are exploited, e.g. in Australia, Thailand, Nigeria and China (Coenraads, 1992a; Guo *et al.*, 1992).

Due to the intense decomposition of volcanic rocks in the humid climate, sapphires have not been found in their host rock (embedded in alkali basalt), but by care-

fully examining the eluvial and alluvial gravel accumulations, the sapphire-bearing primary deposit could be assigned to a specific Tertiary alkali basalt. This coarse-grained, olivine-rich basalt flow always occurs near the contact between Tertiary basalt and the Precambrian basement. Therefore it is suggested that this coarse-grained alkali basalt had been erupted during an early stage of the Tertiary-Quaternary volcanic activity in south-western Rwanda.

The sapphires, concentrated in these eluvial and alluvial deposits are found together with zircon (red-brown and colourless transparent), magnetite, hematite, rutile, pyrite and quartz (originating from the Precambrian rocks).

The Cyangugu sapphires

Mineralogy

Sapphire, basically the blue variety of corundum Al_2O_3 , occurs generally in high alkaline and silica-undersaturated rocks. Two types of geological settings are possible (Levinson and Cook, 1994); the sapphires originate from metamorphic rocks (e.g. dolomite marbles, gneisses) or from magmatic rocks (alkali basalts and pegmatites). Trace elements such as the transition metals Fe, Ti, Cr, V are known to cause a broad variety of colours in sapphires. Either alone or in combination, these ionic impurities may act as chromophores when substituting for Al^{3+} in the

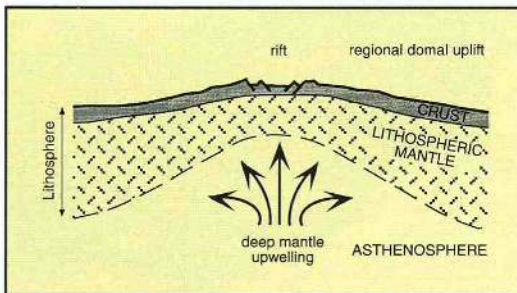


Fig. 6. Schematic profile through the intracontinental rift zone (after: Wilson, 1991).

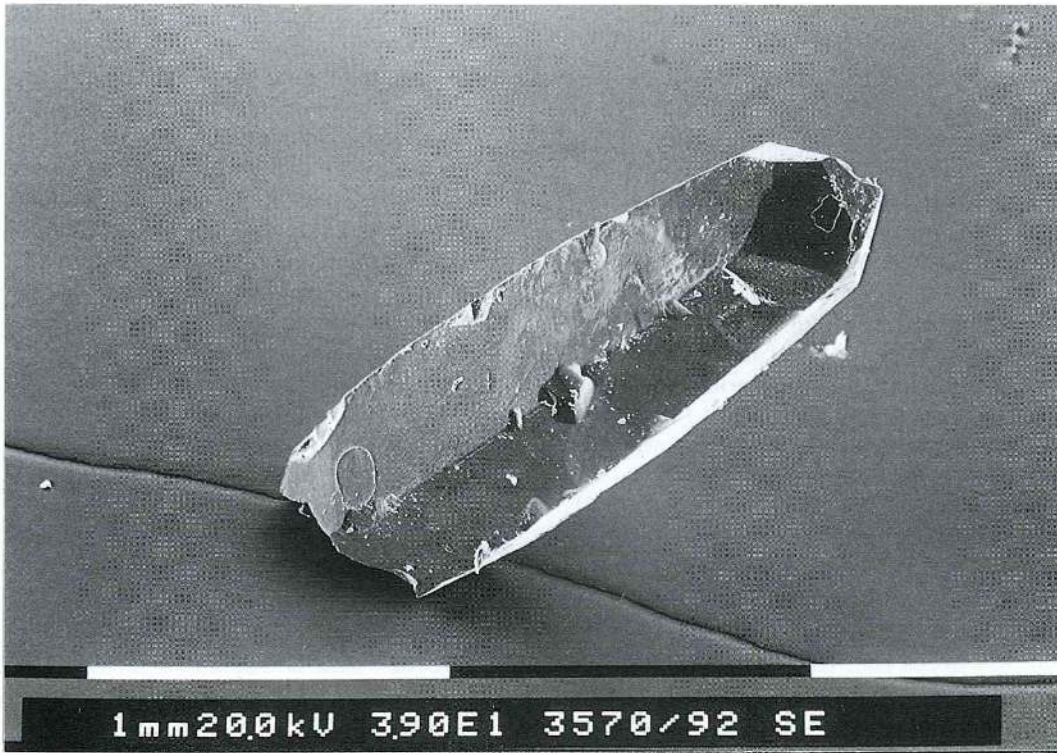


Fig. 8. Slender, prismatic, uncorroded sapphire from the Cyangugu district.



Fig. 9. Faceted and cabochon sapphires from the Cyangugu district. Largest stone is approx. 8 ct.

crystal structure. It has also been observed that these trace elements can actually quit their places in the corundum lattice and concentrate in individual inclusion minerals (Schmetzer, 1986) such as rutile (TiO_2), hematite (Fe_2O_3) or ilmenite (FeTiO_3). As many natural sapphires exhibit growth and colour inhomogeneities, experimental research concentrates on the improvement of the colour in lower quality sapphires by means of heat treatment (Themelis, 1992). During such treatment, former hematite or rutile inclusions may be re-dissolved and their Fe and Ti ions diffuse into the crystal lattice structure where they then may play the role of chromophore elements.

Morphology of rough sapphires

The Cyangugu sapphires are generally 1–8ct in weight and their habit is mostly prismatic-pyramidal. Rhombohedral crystals are much rarer. These observations are in agreement with those made by Kiefert (1987) on sapphire from other basaltic origins (e.g. Nigeria and Australia). She described as significant morphological faces, *a*, *r*, *n* and *z*, whose combination led to tabular, barrel-shaped prismatic and pyramidal crystals (Figure 7).

The surface morphology of the sapphires from the Cyangugu district is in general strongly affected by primary and secondary corrosion or abrasion effects and fractures. Normally the sapphires are broken into flat fragments along the basal plane (0001). Only a few small individuals have preserved their long prismatic shape (Figure 8).

Spectroscopy and chemical analyses

The sapphires from Cyangugu district (Figures 5 and 9) are mainly deep blue but greyish and yellowish tints are also found. The latter are suitable for colour modification by heat treatment (Themelis, 1992).

In sapphires from Rwanda, the blue colour is mainly caused by the $\text{Fe}^{2+}/\text{Fe}^{3+}$ intervalence charge transfer (IVCT) (cf. Karr, 1975; Schmetzer and Bank, 1981; Schmetzer, 1987). A typical UV-visible-near

IR-spectrum reveals three distinct peaks at 375nm, 390nm and 450nm and a broad absorption peak centred at 890nm, which correspond to Fe^{3+} , $\text{Fe}^{3+}/\text{Fe}^{3+}$ ion-pairs and $\text{Fe}^{2+}/\text{Fe}^{3+}$ -IVCT absorption (Figure 10, compare also Fritsch and Mercer, 1993).

In one specimen an absorption shoulder at 560nm (o-vibration spectrum) was observed, caused by the superposition of $\text{Fe}^{2+}/\text{Ti}^{4+}$ -IVCT on the $\text{Fe}^{2+}/\text{Fe}^{3+}$ -IVCT absorption band (Figure 11). But as most spectra reveal no distinct peak at this wavelength (560nm), normally the $\text{Fe}^{2+}/\text{Ti}^{4+}$ -IVCT can be neglected as the cause of colour in these sapphires. The spectral absorption feature at 780nm as observed with o-vibration spectra in Figure 11 remains unexplained (see Schmetzer, 1987).

The strongly dichroic colour of sapphires from Cyangugu district is well illustrated by the different absorption curves in Figure 11.

Qualitative (ED-XFA) and quantitative chemical analyses by the electron microprobe (EMP-WDX) on the same sapphire samples confirmed the spectroscopic information about their trace element content (Table II). Fe is present at constant trace element levels (~0.5 wt% Fe_2O_3), whereas the distribution of Ga varies (~0.03 wt% Ga_2O_3). Ti (and V, Cr, Ca) is nearly at or below detection limit (~0.015 wt% TiO_2) and therefore the blue colour cannot solely be attributed to the Ti. Detection limits below 0.001 wt%, as seen in the literature (Schmetzer and Banks, 1981; Zwaan, 1974), seem quite astonishing in the present context, unless more sensitive analytical methods were used.

Microscopy

Rwanda sapphire samples often exhibit a so-called silk (crystallographically oriented inclusions of submicroscopic dimensions). According to various authors (compare Schmetzer, 1986) rutile needles are oriented parallel to the first order prism of the host corundum. The orientation of

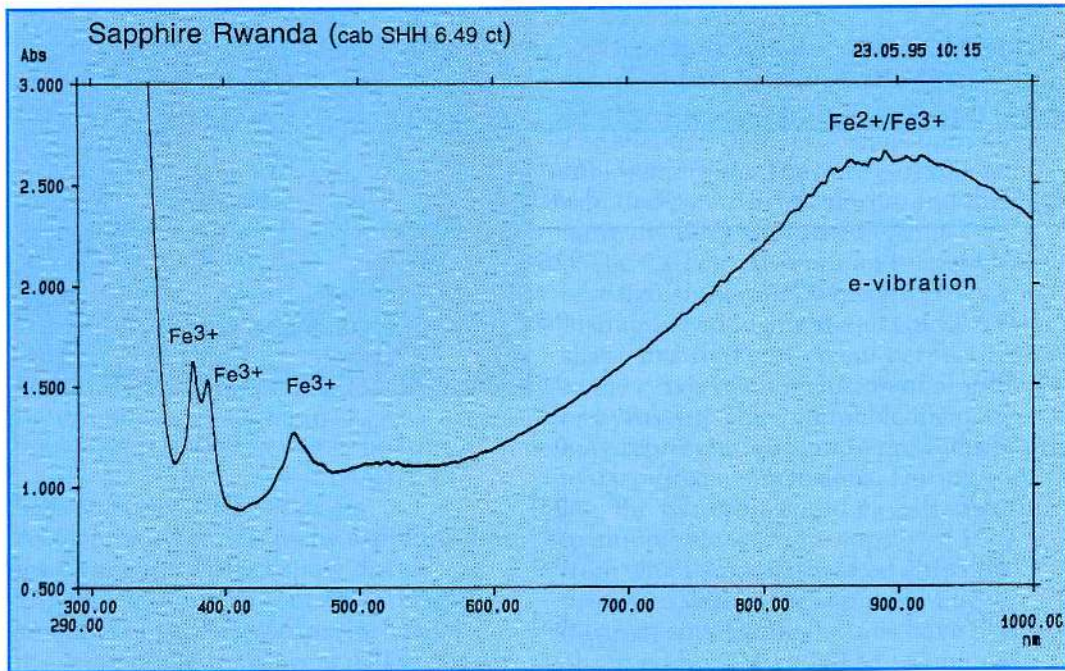


Fig. 10. Wavelength absorption spectra of a sapphire from the Cyangugu district (e-vibration spectrum).

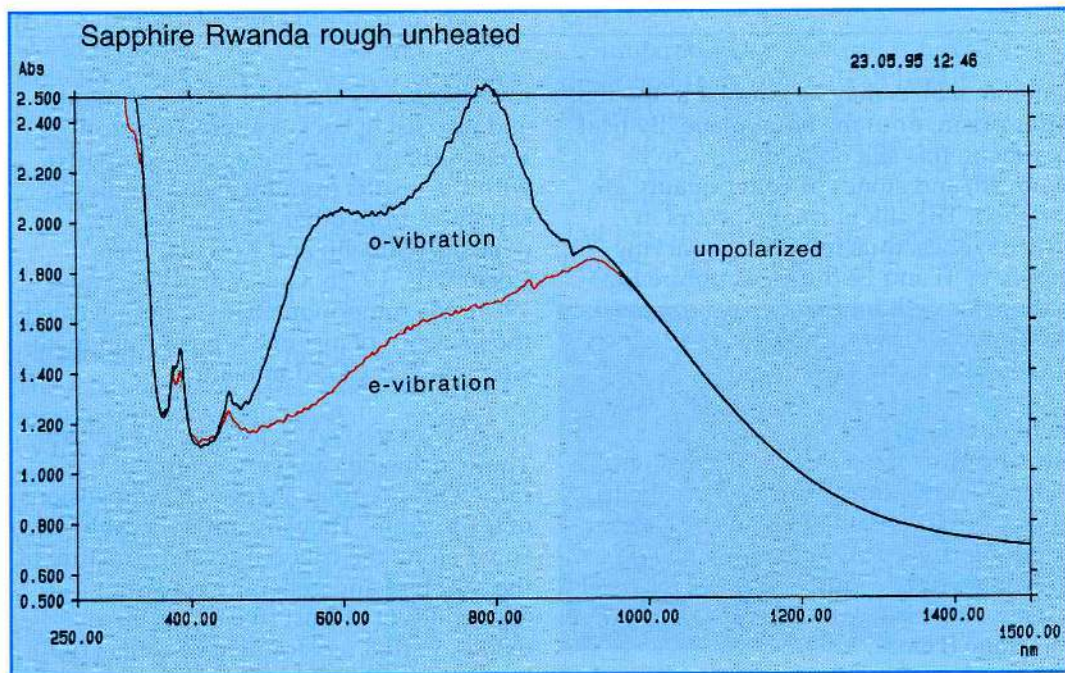


Fig. 11. Wavelength absorption spectra of a sapphire from the Cyangugu district (o- and e-vibration spectra).

Table II: Quantitative chemical analyses (EMP-WDX) of two sapphires from SW Rwanda

| | <i>Mean of 3 analyses</i> | <i>Mean of 5 analyses</i> |
|--------------------------------|-------------------------------|-------------------------------|
| Al ₂ O ₃ | 99.31 | 99.53 |
| Fe ₂ O ₃ | 0.55 | 0.46 |
| TiO ₂ | 0.01 | 0.01 |
| Cr ₂ O ₃ | n.d. | 0.01 |
| V ₂ O ₃ | n.d. | 0.01 |
| Ga ₂ O ₃ | n.d. | 0.04 |
| CaO | n.d. | n.d. |
| Total | 99.87 | 100.06 |

n.d.: not detectable (below detection limit)

hematite tablets may be parallel to the first order prism, or to the basal plane. By heat treatment, this silk occasionally can be removed, and stones of better quality are obtained. The silk normally occurs in growth zones, thus reflecting a varying supply of Ti and Fe during sapphire formation. Growth inhomogeneities can usually be recognized using dark-field optical microscopic techniques.

Inclusion studies

Identification of inclusions in gemstones is of considerable importance, as the inclusions yield information about the genesis of the gemstones and therefore may be – with some restrictions – essential for determining authenticity or even the origin of a gemstone (Hänni, 1994).

A number of solid inclusions, randomly encountered in the sapphires, have been

investigated by the SEM-EDX technique and also using back-scattered electron images (BSE); these have been compared with the results from inclusion studies in sapphires from other alkaline basaltic deposits (Gübelin and Koivula, 1986; Coenraads, 1992b; Guo *et al.*, 1992; Wang, 1988). Microthermometric studies revealed the presence of just one type of fluid inclusion which is CO₂-dominant.

Ti and Fe oxides: rutile, ilmenite and hematite

These inclusions are very common, typically with irregular shapes and dimensions of 0.1 to 2mm. They are not noticeably oriented along the trigonal crystal structure of the sapphire and generally consist of aggregates of at least two of the three oxides. Partial replacement of rutile (TiO₂) by ilmenite (FeTiO₃) at the grain rims can be observed (Figure 12).

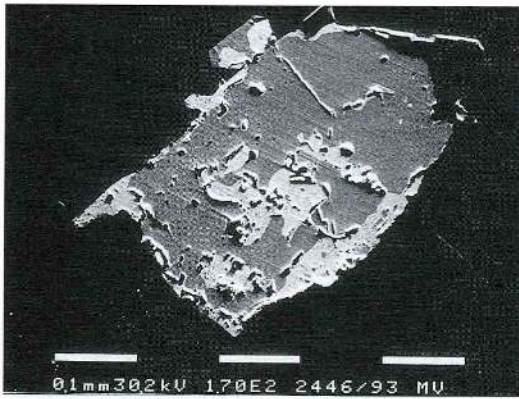


Fig. 12. BSE-micrograph (SEM) of a rutile inclusion, which is partly replaced by ilmenite (white).

Submicroscopic Ti and Fe oxides

As mentioned above, many sapphires from the Cyangugu district show distinct growth zones which contain varying amounts of submicroscopic inclusions – the cause of the translucent (silky) appearance of sapphires. Tiny hematite and rutile crystals may be responsible for this effect, which has been described by many authors from sapphire deposits throughout the world (Hughes, 1990; Gübelin and Koivula, 1986). In the Cyangugu sapphires hematite occurs as tiny brownish inclusions with a 'flaky' (ragged) shape, and rutile occurs as (sub)microscopic, white needle-shaped inclusions (Figure 13).

Genetically, the finely dispersed submicroscopic inclusions may be related to the microscopic Fe- and Ti-oxides. Both reflect the varying Ti and Fe supply during the growth of the sapphires (Figure 14). The relatively large Ti-Fe-oxide inclusions represent protogenetic crystals, enclosed by the growing sapphire. During the following cooling stage, they probably underwent an isochemical replacement reaction where ilmenite was formed from rutile + hematite. In contrast, the submicroscopic Fe-Ti-inclusions are probably a product of the cooling of the sapphires, during which the Fe and Ti ions, formerly dissolved in the corundum lattice, began to precipitate, forming tiny hematite and rutile inclu-

sions, with orientation controlled by the crystal structure of the corundum.

Silicates: pyroxene, amphibole and chlorite

The shape of these inclusions normally is subidiomorphic. They are partially surrounded by a rim of chlorite, and their size normally does not exceed 0.1mm.

The Ca-Fe-pyroxenes and -amphiboles revealed similar EDX-spectra. They were distinguished, using their typical crystal shape in a thin section cut perpendicular to the c-axis of an inclusion of amphibole or pyroxene. The amphibole inclusions may represent retrograde products of primary pyroxene inclusions. During cooling, the pyroxene could have transformed to amphibole with the supply of H₂O from small scale fissures or diffusion processes within the sapphire. Such (healed) small scale fissures have been observed by OM and SEM-techniques. Mica inclusions are also present but are so fragile that they tend to disintegrate during the polishing of the sapphire samples.

Similar kinds of inclusions have been described from other alkali basalt derived sapphire deposits, e.g. in the Australian New England deposit (Coenraads, 1992b), from the Sri Lanka sapphires (Gübelin and Koivula, 1986) and in sapphires from the Shandong Province in China (Guo *et al.*, 1992).



Fig. 13. Crystallographically oriented microscopic rutile inclusions ('silk') in a sapphire from SW Rwanda.

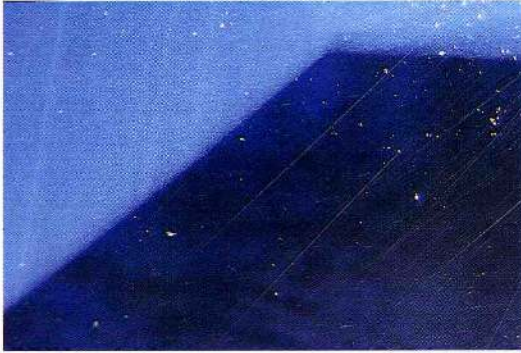


Fig. 14. Growth zoning, represented by submicroscopic inclusions.



Fig. 17. Stress fissures (atoll-structure) around microscopic zircon inclusions.



Fig. 15. BSE micrograph (SEM) of a syngenetic Fe-Zn-Al-spinel.

Spinel

In one sapphire sample a subidiomorphic solid inclusion, surrounded by a chlorite reaction rim was analysed by EDX-spectra and revealed a Mn-bearing intermediate member of the spinel solid solution series between hercynite ($\text{Fe}^{2+}\text{Al}_2\text{O}_4$) and gahnite (ZnAl_2O_4) (Figure 15).

Zircon and cheralite-(Ce)

Zircon and cheralite inclusions in the sapphires may be detected by back-scattered electron image investigations (SEM-BSE). Because they contain elements with high atomic weight (e.g. Zr, Th, REE...), they show a strong brightness contrast relative to the surrounding sapphire (Figure 16).

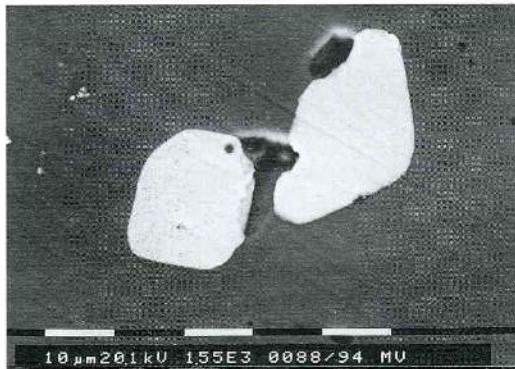


Fig. 16. BSE-micrograph (SEM) of idiomorphic zircon inclusions in sapphire.

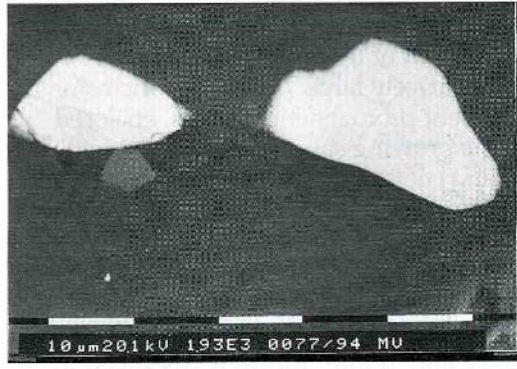


Fig. 18. BSE micrograph (SEM) of cheralite-(Ce) inclusions in sapphire.

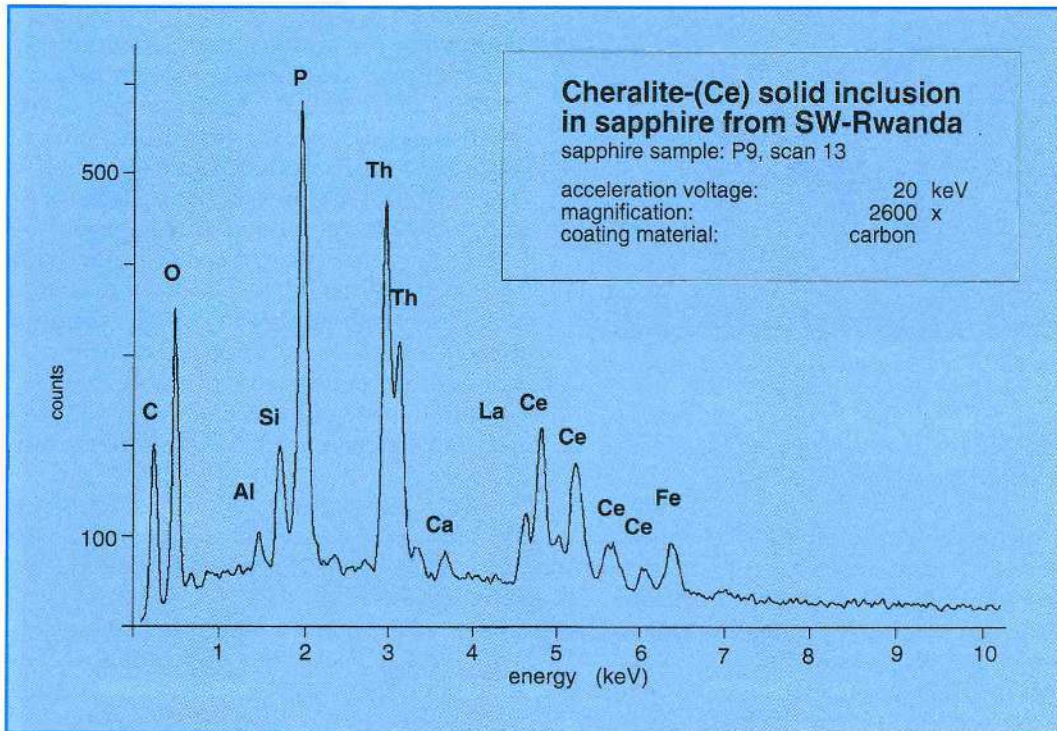


Fig. 19. EDX-spectrum of cheralite-(Ce), a complex phosphate $(Ca,Ce,Th)(P,Si)O_4$, of the monazite group.

The zircon inclusions (0.02 to 0.1mm) are characterized by a more or less idiomorphic shape, suggesting proto to syngenetic growth relative to the sapphire. They commonly occur in small groups and are surrounded by stress fissures in the host sapphire, typical for metamict inclusions (Gübelin and Koivula, 1986) (Figure 17).

One inclusion, adjacent to some zircon inclusions, was identified by SEM-EDX as cheralite-(Ce), a complex thorium-phosphate $(Ca,Ce,Th)(P,Si)O_4$, belonging to the monazite group (Figures 18 and 19).

Stress fissures around this inclusion are partially filled with a mineral (probably goethite $\alpha\text{-FeO(OH)}$), causing a pale brown halo (Figure 20).

Fluid inclusions

Microthermometric studies (by B. Bruder) of the sapphires revealed the presence of CO_2 dominated fluid inclusions as fillings

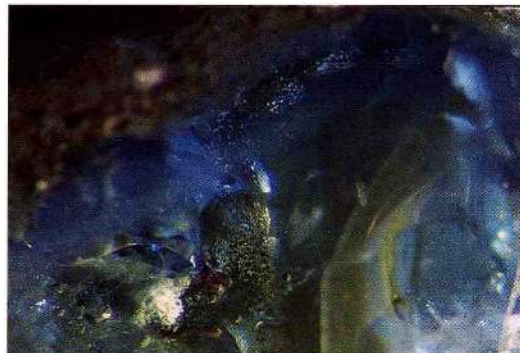


Fig. 20. Fe-hydroxide in fissures around cheralite-(Ce) inclusions.

of voids, negative crystals and 'fingerprints'. At room temperature, most of the fluid inclusions are monophasic (pure CO_2 with a maximum density of $0.95g/cm^3$). This is consistent with results from fluid inclusion studies on other volcanic sapphires. No distinctive fluid composition

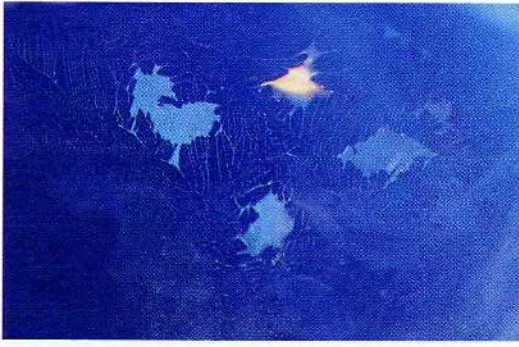


Fig. 21. Fluid inclusions along a healed fissure in a sapphire from the Cyangugu district.

and density was discovered for the Rwanda sapphires (Figure 21).

Inclusions similar to those observed in sapphires from the Cyangugu district have been described by many authors from analogous sapphire deposits in volcanic provinces. As Webster and Anderson (1983) and Hänni (1994) suggest, using the inclusions alone is insufficient to indicate the geographic origin of a gemstone. They merely give information about the geological and geochemical conditions during their genesis (for the Rwanda sapphires: during the continental volcanic activity along the western part of the East African rift suture).

Surface features

There are two main processes that have affected the surfaces of the Rwanda sapphires. *Primary corrosion*, a mainly chemical process during volcanic activity, and *secondary abrasion and fracturing*, mechanical impact processes which occurred during the erosion of basalts and subsequent transport of the sapphires to the alluvial deposit.

The primary corrosion features were studied with the SEM on eight randomly selected samples.

The genesis of sapphires from alkali basalts is still under debate. The model generally accepted is that they were formed at the conditions prevailing in the

lower crust or upper mantle (high temperature and pressure) in a high aluminium environment. Most authors (Coenraads, 1992b; Guo *et al.*, 1992; Levinson and Cook, 1994) suggest, however, that the sapphires were not formed in the alkali basalt itself. The corrosion features on the surfaces of sapphires are interpreted as reactions of sapphire xenocrysts in disequilibrium with the basic magma (alkali basalt). If correct, this model implies that the basaltic magma acted merely as a transport medium and not as the parent magma of the sapphires. During the rise of the carrier magma, the sapphires were corroded by reactions with the melt.

Most Cyangugu sapphires show distinct primary corrosion features. The surface is typically rough and marked by many indentations (Figure 22). On the basal plane, there are triangular indentations, which are typical corrosion features of trigonal minerals.

One specimen is covered with a thin brownish layer (Figure 23), probably consisting of a Fe-hydroxide (α -FeO(OH)), which may have been derived originally from native iron.

Another specimen shows a very specific corrosion, not previously recorded. The whole surface is covered by a randomly oriented needle-like pattern (Figures 24 and 25), interpreted as due to long prismatic plagioclases, which covered the sapphire during its transport by and in the plagioclase-rich alkali basalt. The plagioclase partly protected the sapphire from primary corrosion in the magma (Figure 26) but due to the intense weathering of the basalt, it has since decomposed, and only the sapphire remains (cf. Coenraads, 1992a).

This specific corrosion feature sheds some light onto the relation between sapphire genesis and alkali basaltic magmatism. Plagioclases that are probably responsible for the needle-like surface pattern are virtually absent as solid inclusions within the sapphires from Cyangugu dis-

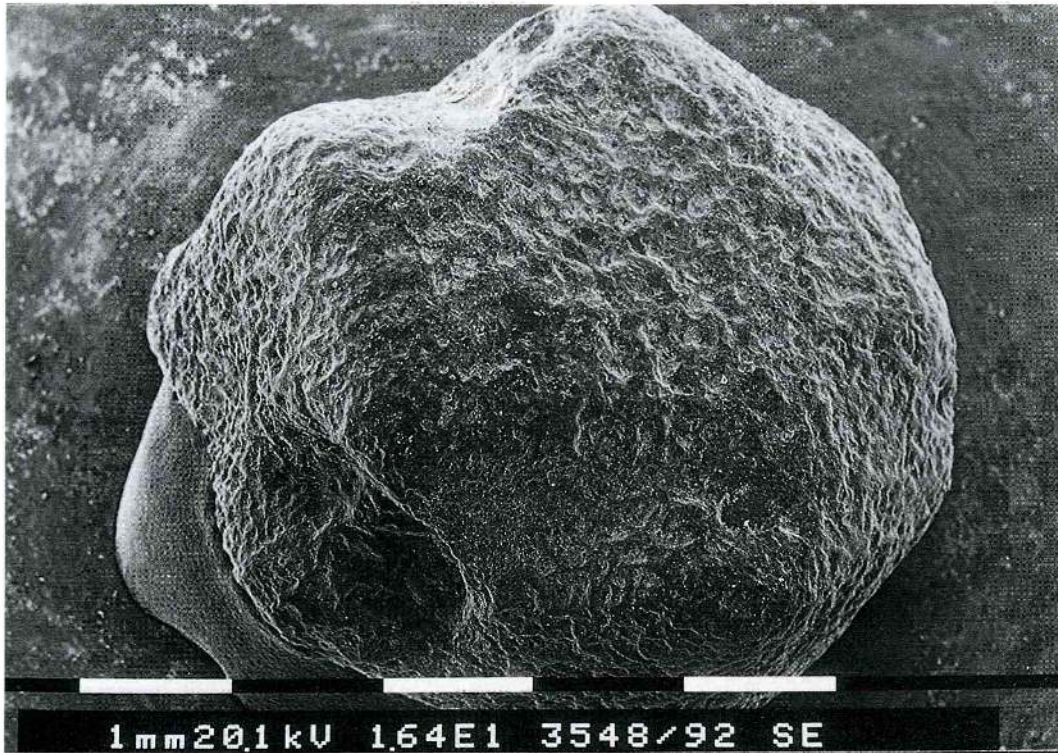


Fig. 22. SEM-micrograph of a strongly corroded sapphire from the Cyangugu district.

trict. Therefore it is suggested that these sapphires originate from a source other than the alkali basalt magma. Whether the incorporation of sapphires into the ascending alkali basalt occurred by magma mixing processes (magmatic origin of sapphires) or by supply of deep crustal rock fragments (metamorphic origin of sapphires) is not yet established (cf. Levinson and Cook, 1994). Radiometric age dating of both the alkali basalt and the sapphires (U-Pb-dating of zircon inclusions) could reveal further information on sapphire genesis (cf. Coenraads *et al.*, 1990).

Conclusions

Sapphires from the Cyangugu district (SW Rwanda) originate from a specific alkali basalt, which has been erupted during Tertiary volcanic activity along the East African rift. Prospecting has established several alluvial-type sapphire

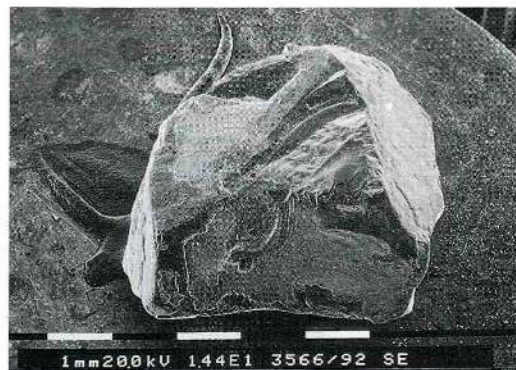


Fig. 23. SEM-micrograph of a sapphire, partially protected by a Fe-hydroxide layer.

deposits, which may have potential for future mining.

The sapphires normally are deep blue and commonly show a so-called 'silky' appearance. Three different types of solid inclusions which are typical for corundum

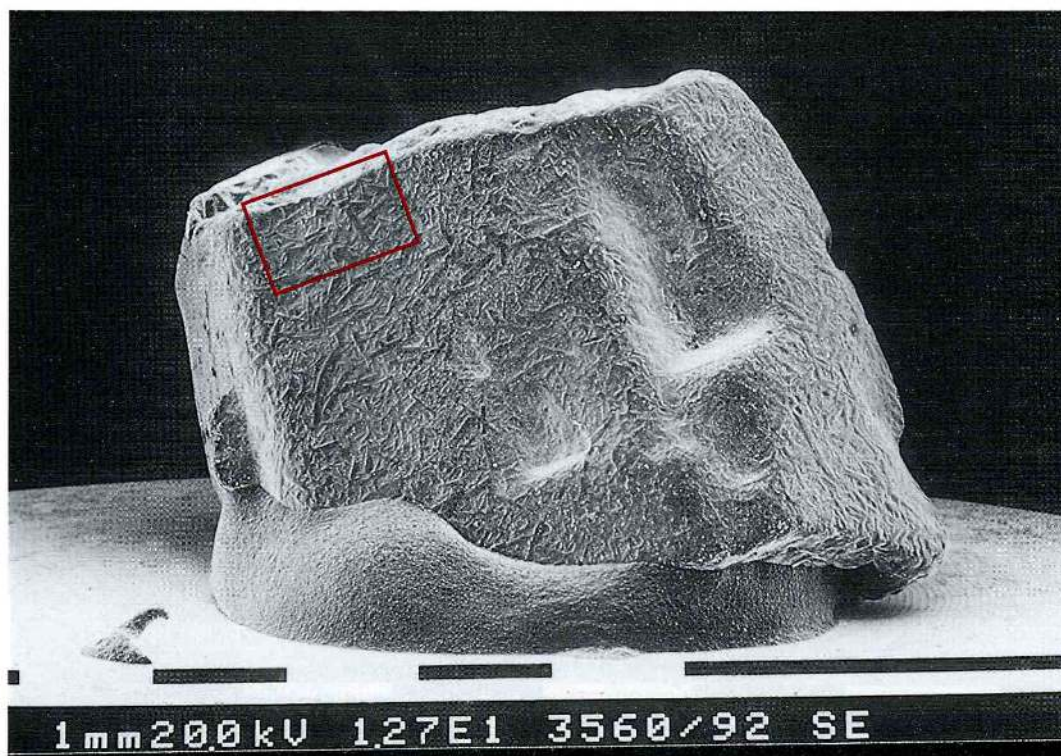


Fig. 24. SEM-micrograph of a specific needle-like corrosion feature on a sapphire of the Cyangugu district.



Fig. 25. SEM-micrograph of the marked area of the same sample under higher magnification.

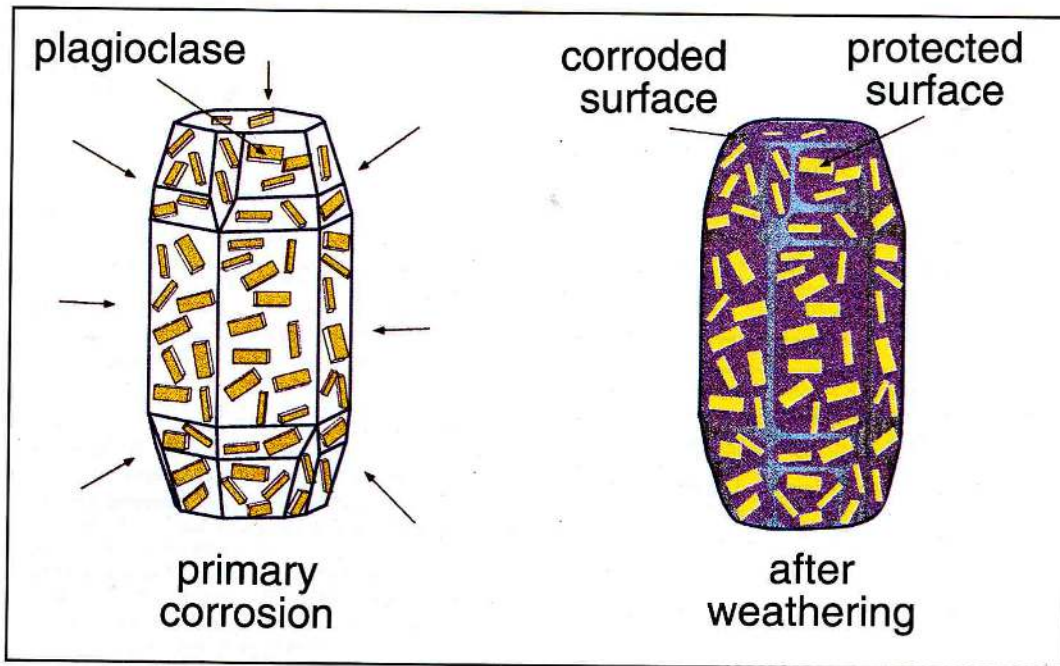


Fig. 26. Scenario explaining the genesis of the corrosion feature shown in Figures 24 and 25:

- (a) the sapphire was covered by plagioclases in the ascending alkali basalt, protecting the gem stone partly from corrosion;
- (b) subsequently, the plagioclases have been weathered during erosion of the erupted basalts.

from volcanic provinces have been distinguished. The sapphires often show signs of pronounced corrosion, and a needle-like pattern is interpreted as the relic of a former coating of plagioclase crystals. There is close similarity of these sapphires with those derived from other basaltic deposits, and an unambiguous identification of sapphires specifically from the Rwanda deposit is not possible.

Until now, sapphires from the Cyanguu district in SW Rwanda have not been well known on the gem market, but if the political situation stabilizes they may well become much more familiar to stone dealers and gemmologists.

Acknowledgements

We would like to thank Dr R Gieré (Min. Petrogr. Institute, University Basel) for his critical review of this paper, and Dr L. Kiefert (SSEF, Basel) for analytical assistance in taking both optical and ED-XRF-

spectra and for useful discussions. Thanks also go to J.F. Damon (Twin Gems Co., Washington DC) for financial support and to J. Stähli (Bern) for the loan of faceted sapphires from SW Rwanda and for his encouragement

References

- Barot, N.R., and Harding, R.R., 1994. Pink corundum from Kitui, Kenya. *Journal of Gemmology*, **24**, 3, 165-72
- Bruder, B., 1995. Charakterisierung von Rubinen und Saphiren mit Hilfe von Flüssigkeitseinschlüssen. Diploma thesis, Univer. Freiburg, Germany (unpublished)
- Cahen, L., Snelling, N.J., Delhal, J., Vail, J.R., 1984. *The geochronology and evolution of Africa*. Clarendon Press, Oxford, p.179 ff
- Coenraads, R.R., 1992a. Surface features on natural rubies and sapphires derived from volcanic provinces. *Journal of Gemmology*, **23**, 3, 151-60
- Coenraads, R.R., 1992b. Sapphires and rubies associated with volcanic provinces: inclusions and surface features shed light on their origin. *Australian Gemmologist*, **18**, 3, 70-8
- Coenraads, R.R., Sutherland, F.L., and Kinny, P.D., 1990. The origin of sapphires: U-Pb dating of zircon inclusions sheds new light. *Mineralogical Magazine*, **54**, 113-22
- Fritsch, E., and Mercer, M., 1993. Blue color in sapphire caused

- by $\text{Fe}^{2+}/\text{Fe}^{3+}$ intervalence charge transfer. *Gems & Gemology*, **22**, 3, 151
- Gübelin, E.J., and Koivula, J.I., 1986. *Photoatlas of inclusions in gemstones*. AB-edition, Zurich, Switzerland. p.186 and 324 ff
- Guo, J., Wang, F., Yakoumelos, G., 1992.. Sapphires from Changle, in Shandong province, China. *Gems & Gemology*, **28**, 4, 255-60
- Hänni, H.A., 1986. Korunde aus dem Umba-Tal, Tansania. *Z.Dt. Gemmol. Ges.*, **35**, 1/2, 1-13
- Hänni, H.A., 1994. Origin determination for gemstones: possibilities, restrictions and reliability. *Journal of Gemmology*, **24**, 3, 139-48
- Hughes, R.W., 1990. *Corundum*. Butterworth-Heinemann, London
- Kanis, J., and Harding, R.R., 1990. Gemstone prospects in Central Nigeria. *Journal of Gemmology*, **22**, 4, 195-202
- Karr, C., 1975. *Infrared and Raman spectroscopy of lunar and terrestrial minerals*. Academic Press, New York. p.39 ff
- Kiefert, L., 1987. Mineralogische Untersuchungen zur Charakterisierung und Unterscheidung natürlicher und synthetischer Sapphire. Diploma thesis, Univer. Heidelberg, Germany (unpublished)
- Levinson, A.A., and Cook, F.A., 1994. Gem corundum in alkali basalt: origin and occurrence. *Gems & Gemology*, **30**, 4, 253-62
- Putnis, A., 1992. *Introduction to mineral sciences*. Cambridge University Press, USA
- Schmetzer, K., 1986. *Natürliche und synthetische Rubine*. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany
- Schmetzer, K., 1987. The cause of colour in blue sapphire - a discussion. *N. Jb. Miner. Mh.*, **8**, 337-43
- Schmetzer, K., and Banks, A., 1981. The colour of natural corundum. *N. Jb. Miner. Mh.*, **2**, 59-68
- Themelis, T., 1989. A new sapphire deposit: Turkana, Kenya. *Gem Digest*, **2**, 4, 32-4
- Themelis, T., 1992. *The heat treatment of sapphires*. Word Graphics Inc., USA (distributed by the author)
- Wang, F., 1988. The sapphires of Penglai, Hainan Island, China. *Gems & Gemology*, **24**, 3, 155-60
- Webster, R., and Anderson, B.W., 1983. *Gems*. Butterworths, London. pp.74-98
- Wilson, M., 1991. *Igneous petrogenesis*. Unwin Hyman, London. p.325 ff
- Zwaan, P.C., 1974. Garnet, corundum and other gem minerals from Umba, Tanzania. *Scripta Geol.*, **20**, 1-41

Appendix

Analytical conditions

References for some of the analytical techniques applied are given in Hänni (1994). Two sapphire samples were cut and two faces polished parallel to the optic axis in order to record absorption spectra. With a Hitachi 4001 spectrophotometer the absorption features between 250 and 900nm (VIS-IR) were measured. Polarization filters were used in the visible part.

The scanning electron microscope, attached to an energy-dispersive X-ray spectrometer (SEM-EDX) is a powerful tool to obtain morphological and chemical information (Putnis, 1992). All the SEM investigations were performed on a Philips 515 instrument (20kV). Thin sections with randomly oriented, polished planes were prepared from ten samples to determine the nature of solid inclusions. The samples were coated with carbon for SEM-EDX analyses and back scattered electron imaging (BSE). Eight rough samples were sputtered with gold (20nm thickness) for SEM investigations of surface features.

Qualitative X-ray fluorescence analyses (ED-XRF) were carried out by a Philips combined Spectrace X-ray fluorescence spectrometer (25 kV, 0.3 mA, Al primary filter) in order to determine the trace elements present in the sapphires from SW Rwanda. For quantitative chemical information, two sapphires were analysed by a wavelength-dispersive electron microprobe (JEOL JXA-8600) operated at 20 kV and with a specimen current of 10 nA measured on a Faraday cage (EMP-WDX). Seven reference standards (Al, Fe, Ti, Cr, V, Ga, Ca) of well characterized natural and synthetic compounds were used and all the data were fully corrected for matrix effects by PROZA-computer program.

Two thin slices (approximately 0.3mm thick) of sapphires were investigated under a Leitz Ortholux microscope equipped with a Reynolds heating-freezing stage for microthermometry. The measurements were performed on 75 fluid inclusions by Bernard Bruder (Univ. Freiburg, Germany) who investigated fluid inclusions in corundum from various sources for his university diploma in mineralogy.