Utilisation of sillimanite minerals, their geology, and potential occurrences in Norway – an overview

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The aluminium-silicate polymorphs sillimanite, andalusite and kyanite decompose to a mixture of mullite and silica glass during calcination. Mullite is an essential component of high-alumina refractories forming the inner lining of furnaces and high-temperature vessels widely used in the production of metals, ceramics, glass and cement. Sillimanite, andalusite and kyanite constituted 2%, 74% and 24%, respectively, of the total western world's production of sillimanite minerals in 1998 of a total of about 401 000 tonnes, of which about 95% was consumed by the refractory industry. The sillimanite minerals are mined mainly in South Africa (62%; andalusite), USA (23%; kyanite) and France (11%; andalusite), whereas the major consumers are found in the major iron- and steel-producing areas of the world. Production has declined over the last decade, due mainly to cutbacks in iron and steel production. Most economic deposits of sillimanite minerals can be classified as metamorphogenic and include contact-metamorphic andalusite deposits, stratabound podiform deposits of massive (corundum)-sillimanite and (corundum)-kyanite rocks and stratiform deposits of kyanite quartzites. The former occur within metapelitic sequences in the contact aureoles of plutonic massifs, whereas the two latter in most cases are interpreted as representing metamorphosed high-alumina sediments, derived from hydrothermal alteration centres in subaerial felsic to intermediate volcanites. All of these deposit types have also been recognised in Norway. The most promising occurrences are the andalusite schists within the contact aureoles of the Fongen-Hyllingen and Øyungen Gabbro Complexes in the Caledonides of Central Norway.

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Introduction

The term 'sillimanite minerals' has become firmly entrenched in the industrial minerals trade in the Anglo-Saxon part of the world as representing all three natural polymorphs. This is mainly because the refractory raw-material imported from India in the early years of the refractory industry was sillimanite. In a similar way, kyanite minerals have become the common name for the group in the USA whereas andalusite appears to be often used in a similar group sense in Russia and the former Soviet republics (Varley 1965). Sillimanite minerals comprising sillimanite, andalusite and kyanite are naturally occurring anhydrous aluminium-silicate polymorphs with the chemical formula Al_2SiO_5. They are all common rock-forming minerals differing somewhat in crystallographic characteristics and thereby in physical properties. The industrial use of sillimanite minerals is especially related to their unique chemical composition, stability at high temperatures and transformation to mullite-rich aggregates utilised as refractory material.

The aim of the present paper is to give a review of the utilisation, trade, consumption, production and raw material specifications of sillimanite minerals which are essential to exploration geologists in assessing the economic viability of deposits of these minerals. Secondly, to describe the geology of some representative examples of economic deposits together with models for their formation which will be used as a basis for evaluating possible exploration targets in Norway.

Sillimanite minerals, Al_2SiO_5

Alumino-silicate polymorphs with a stoichiometric composition of 62.93% Al_2O_3 and 37.07% SiO_2. The crystal lattices are composed of chains of Al-O octahedra along the z-axis linked sideways by chains of alternating Si-O and Al-O tetrahedra (sillimanite, orthorhombic), Si-O tetrahedra and distorted Al-O octahedra (andalusite, orthorhombic) or of Si-O tetrahedra and the remaining Si, Al and O atoms (kyanite, triclinic). The lattices give room for only limited substitution by Fe, Mn, Ti and Cr; mainly in andalusite and kyanite. The bladed, needle-shaped and long prismatic crystals show variable colours in mainly shades of grey, pink, yellow and blue. The sillimanite minerals show hardness and density in the ranges 5.5-7.5 and 3.13-3.65, respectively, with andalusite having the lowest and kyanite the highest density. *Chiastolite* is a variety of andalusite which has cross-sections with dark carbonaceous inclusions distributed in a cruciform pattern, whereas *fibrolite* refers to the fine-grained fibrous variety of sillimanite (Deer et al 1966).

Mullitisation

The sillimanite minerals decompose irreversibly to mullite when burnt at high temperatures (calcination), according to the reaction:

$$3Al_2SiO_5 \rightarrow Al_6Si_2O_{13} + SiO_2$$
$$\text{(sillimanite)} \quad \text{(mullite)} \quad \text{(tridymite)}$$
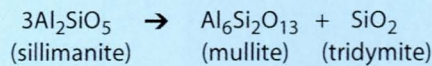
The end product of this reaction is an aggregate comprising interlocking, acicular crystals of mullite (~88%) in a matrix of silica or tridymite glass (~12%), which remains stable until the temperature is raised above 1800°C (Varley 1965, Potter 1991). Complete mullitisation of kyanite and andalusite occurs normally in the temperature range 1350-1380°C and 1380-1400°C respectively, whereas sillimanite breaks down at higher temperatures, i.e. around 1550°C. During calcination, kyanite increases in volume by 16-18%, sillimanite by 6-7% and andalusite by 4-5% (Anon. 1988, McMichael 1990). As a consequence, the mixtures of mullite and silica produced have lower densities than those of the original minerals.

Utilisation

Refractory use

About 95% of the sillimanite minerals produced are used as raw material for the refractory industry in the manufacturing of non-basic, high-alumina refractories (Roskill 1990, O'Driscoll & Harries-Rees 1993). The refractory characteristics of these minerals is related to their ability to form the refractory mullite phase which combines high strength with resistance to physical and chemical corrosion at high temperatures. Mullite is therefore an essential component of refractories forming the inner lining of furnaces and high-temperature containers widely used in the manufacturing of metals, glass, ceramics and cement.

The sillimanite minerals, raw or calcinated, are especially used in the manufacturing of refractory bricks and shapes as well as of mortars or cements, ramming and gunning mixtures and castables (refractory concretes) used in the construction of joint-free and self-supporting monolithic refractory linings. Sillimanite and andalusite, which only expand by 4-7 volume % during mullitisation, have the advantage that they can be used in their raw state. Since calcination requires energy, the use of these minerals represents substantial cost savings in respect to kyanite which expands considerably during heating. Calcination is therefore a prerequisite for kyanite in a number of refractory applications. However, natural kyanite is preferentially used for monolithics and as a component (10-40%) of refractory clay mixtures (bricks, mortars, castables, etc.) in order to counteract shrinkage of the clay binder during firing (Bennet & Castle 1983).

The major end use of sillimanite minerals is in the iron and steel industries which consume 60% or more of the mullite refractories (Dickson 1996). They are used in critical areas of furnaces, steel degassing chambers, soaking pits and many types of auxiliary pouring and handling equipment. The second most important application is as furnace linings in the non-ferrous metallurgical and glass industries as well as in ceramic and cement kilns. Other uses, minor in volume terms, include foundry-mould facings, combustion chamber linings, burner bodies, pyrometer tubes and welding rod coatings (Roskill 1990).

Refractories

Refractories are materials that remain physically and chemically stable at high temperatures under extreme conditions of heat and corrosion (O'Driscoll & Harries-Rees 1993). Those derived from sillimanite minerals belong to the group of high-alumina refractories, i.e. refractories exceeding 47.5% Al_2O_3 (O'Driscoll & Harries-Rees 1993). They are used in acid rather than basic environments (non-basic refractory) and have high degrees of resistance to creep deformation, thermal shock and slag attack. Other important properties are high thermal conductivity, low coefficients of expansion, low porosity and high resistance to reducing atmospheres, fluxing by volatile alkalies and spalling (McMichael 1990).

Non-refractory use

Subordinate amounts of the produced sillimanite minerals (c.5%) have non-refractory uses (Roskill 1990). Raw and calcinated minerals are utilised in the manufacture of high-tension insulators and other electrical ceramics, ceramic tile body components, sanitary ware, ceramic honeycombs, blown aluminium-silicate high-temperature insulation, brake linings, glass melt additives, spinnable mullite fibres, grinding media and extrusion dies. Sillimanite minerals are also locally used to produce Si-Al alloys, metallic fibres and selected aluminium oxides (Wu 1990). High-purity and fine-grained (< 200 mesh) kyanite is preferentially used by ceramic manufacturers of wall tile and sanitary porcelain to offset shrinkage and cracking after firing (Bennet & Castle 1983).

Consumption and production

The consumption of sillimanite minerals is concentrated in the relatively highly industrialised areas where refractories are manufactured and which in turn are typically close to the major iron and steel producing regions in the world (Roskill 1990). The principal consumers in the western world are therefore found in the EU, North America, the Far East and South Africa, whereas mining of these minerals is controlled by five major producers situated in South Africa (andalusite), USA (kyanite) and France (andalusite) (Fig. 1). The majority of sillimanite minerals produced in other countries such as Australia, Brazil, China, India, Ukraine and Zimbabwe is mostly for domestic consumption. As a consequence, the trade in sillimanite minerals is international.
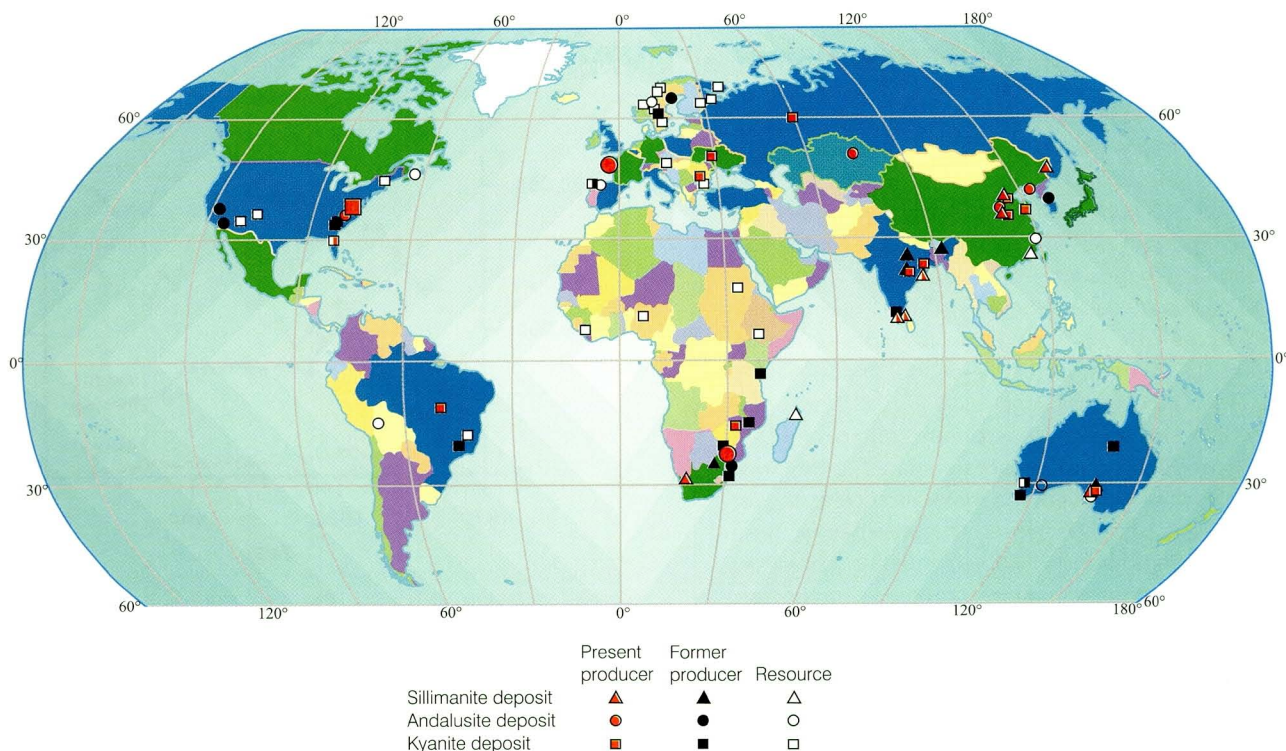
Fig. 1. Map showing the distribution of high-grade aluminium-silicate deposits in the world, including past and present producers and possible resources. Compiled mainly from Roskill (1987, 1990) and Varley (1965). Countries in dark blue and green have an annual production of steel exceeding 8 Mt. Supergene deposits are shown by divided symbols.

Norwegian consumption

The annual import of sillimanite minerals, mainly andalusite, increased from 2650 tonnes in 1994 to 3530 tonnes in 1996, whereas that of a variety of calcinated products (mullite) reached 67 tonnes in 1996. The major part of the sillimanite minerals is used by Borgestad Fabrikker A/S, situated near Skien in southern Norway, in the manufacturing of refractory bricks and castables with Al_2O_3 contents of 35-95%. Since the steel industry is small in Norway, major domestic markets for refractory bricks and monolithics are found in the ferro-alloy industry, primary aluminium plants and also in the porcelain industry (Harries-Rees 1993).

The refractory industry is presently plagued by over-capacity due to the general downturn in iron and steel production and to technological improvements leading to increased longevity of the refractories and decline in refractory consumption per tonne of steel produced (Harries-Rees 1993, O'Driscoll 1999). Thus, there is intense competition for markets at various levels of the trade in sillimanite minerals and mullite refractories, i.e. between high-alumina refractories and other non-basic refractories, between different types of high-alumina refractories and between members of the sillimanite minerals. However, over the last decade developments in the iron and steel production have resulted in ever increasingly severe furnace conditions. This has been in favour of the sillimanite minerals by a move away from fire-clay materials to those containing higher alumina contents.

The high-alumina refractory market is very price sensitive and the choice of refractory is usually based on cost-effectiveness and availability rather than unique physical and chemical properties. Thus, where available, local raw materials and products are favoured over those imported. Therefore, andalusite-based refractories are preferentially used in the refractory industry of South Africa and France and kyanite-based refractories in the USA. This prohibits the use of alternative and technically superior materials, except where high temperatures and high loads make them irreplaceable (McMichael 1990).

Sales of sillimanite minerals are customarily arranged in buyer-seller bargaining and are based on mineral product specifications such as chemical composition (alumina contents, alkalies, etc.), physical characteristics (grain size, density, etc.) and performance in refractory tests and simulated service tests. The strong competition with other refractory raw materials has a major impact on keeping the prices at a relatively stable level. Guidelines for recommended prices are quoted monthly in several publications, e.g. in Industral Minerals. Presently, the prices per metric tonne mineral concentrate fall within the range $135-230 (March 2000). They increase in sympathy with alumina content and grain size and are higher for andalusite concentrates than for those of kyanite at similar alumina levels.

Over the last three decades, the western world's production continued to increase and reached an all-time maximum in 1989 at about 500 000 tonnes, subsequently declining to an annual production of 360 000-370 000 tonnes in 1993-

Mineral product specifications for refractory use

One of the most important properties of high-alumina refractory materials is their creep resistance which is related to the amount of mullite and the presence of fluxing impurities, especially contained in the gangue minerals of the mineral concentrates. The chemical composition of commercial refractory-grade raw materials as shown in Table 1, is characterised by 54-70% Al_2O_3 and low contents of fluxing oxides, i.e. generally <1% Fe_2O_3, <2% TiO_2, <0.5% Na_2O+K_2O and <0.5% $MgO+CaO$ (Roskill 1990). Alumina contents above the maximum content of 62.9% Al_2O_3 for sillimanite minerals are related to the presence of other high-alumina minerals such as corundum and diaspore. However, the presence of these minerals is not necessarily objectionable; rather, they may enhance the refractory properties of the raw material (Potter 1985).

Another important property is the grain size of the mineral product. Refractory bricks should contain about 60 % of coarse grain-size material mixed with finer grain sizes and different types of binders in order to give the bricks the required density and strength under load (McMichael 1990). However, the lower costs of production and installation of monolithic refractories, which are made totally from fine-grained fractions of sillimanite minerals, have resulted in a trend away from the use of bricks to the application of monolithic linings wherever possible (Harries-Rees 1993). The coarse-sized grades, previously highly sought after, are therefore becoming gradually less important.
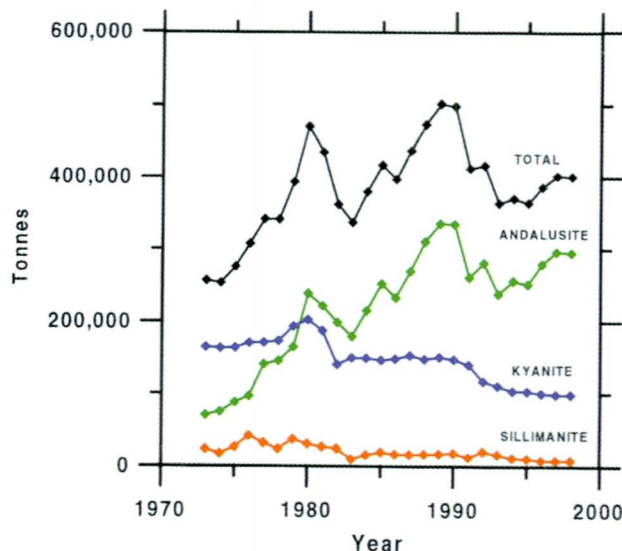

Fig. 2. Diagram showing the annual western world's production of sillimanite, andalusite and kyanite as well as the total tonnage over the period 1973-1998. Production numbers compiled from Roskill (1987, 1990), Potter (1991, 1994, 1998) and estimations given by Dickson (1996).

WESTERN WORLD'S PRODUCTION IN 1998	
	Metric tonnes
AUSTRALIA	
Sillimanite	100
Kyanite	800
BRAZIL	
Kyanite	600
FRANCE	
Andalusite	45000
INDIA	
Sillimanite	7500
Kyanite	6700
SOUTH AFRICA	
Andalusite	250000
USA	
Kyanite	90000
ZIMBABWE	
Kyanite	50
Total production	**400750**
Total, sillimanite	**7600**
Total, andalusite	**295000**
Total, kyanite	**98150**

Table 2. The western world's production of sillimanite minerals in 1998. Based on data from Potter (1998).

1995 before climbing to the present level of about 401 000 tonnes (Fig. 2). Sillimanite, andalusite and kyanite constitute 2%, 74% and 24%, respectively, of the total tonnage produced in 1998. South Africa accounted for 62% of this total whereas USA and France provided 23% and 11%, respectively (Table 2). The remaining 4% is produced mainly in India with additional minor contributions from Brazil, Australia and Zimbabwe. Mining of sillimanite has declined steadily from c.41 000 tonnes in 1976 to 7600 tonnes in 1998. India is the main producer, whereas Australia provides only about one hundred tonnes. Andalusite production has grown strongly, passing kyanite as the most important polymorph in 1980. Today, most of the andalusite is produced from six deposits in South Africa (250 000 tonnes) and one in France (45 000 tonnes). The western world's production of kyanite is characterised by one leading producer in USA and several smaller. Production has declined by 33% since 1990, to c.98 000 tonnes in 1998. 92% of this is mined by Kyanite Mining Cooperation in Virginia, USA.

Name of deposit	Swartkoppies	Glomel	Havercroft	Halsjöberg
Country	South Africa	France	South Africa	Sweden
Sillimanite mineral	**Sillimanite**	**Andalusite**	**Andalusite**	**Kyanite**
Quality	High-grade	Kerphalite KA	Grade 1 Macle	High-grade
SiO_2		37.50-38.60	38,20	35,80
Al_2O_3	71.00-72.00	59.00-59.50	61,40	59,80
TiO_2	3,10	0.20-0.28	0,11	0,64
Fe_2O_3	1,30	0.90-1.10	0,61	(Fe, tot.) 1.30
MgO + CaO		0.24-0.45	(CaO) 0.05	0,40
$Na_2O + K_2O$		0.23-0.45	(K_2O) 0.12	0,03
Grain size	25-75 mm	0.3-1.6 mm	>4 mm	60-325 mesh
References	Roskill (1987)	Roskill (1987)	Human and Collins (1986)	Anon. (1986)

Table 1. Chemical composition (weight %) and grain-size range for some selected commercial products of sillimanite minerals.

Data acquisition

Data regarding annual production, mining capacity and consumption are not readily available for the public and are in many instances withheld by both the individual mining companies and the governments of the producing countries. The latter is usually the case for China and the former communist countries (Eastern Bloc) and even for many countries in the western world. It reflects the crucial importance of sillimanite minerals in the production of metals and especially iron and steel and thereby the country's ability to maintain production in periods with international crises and military conflicts, i.e. the sillimanite minerals are of strategic importance. Secondly, the companies want to avoid disclosing competitive advantages. The production numbers given in Table 2 and Fig. 2 for the western world are therefore partly estimates.

Natural occurrences of sillimanite minerals

Sillimanite minerals are commonly encountered in peraluminous metamorphic, plutonic and volcanic rocks and their weathering products. Their stability fields are depicted in Fig. 3. They are frequently retrograded to muscovite, sericite, pyrophyllite, paragonite and/or margarite by interaction with hydrothermal fluids. The sillimanite minerals have a relatively high resistance to weathering leading to enrichment in residual soils and local accumulations in alluvial and beach-sand deposits. The most typical hard-rock occurences of sillimanite minerals comprise:

- Kyanite, sillimanite and andalusite in metapelites and quartzites of regional metamorphic terranes.
- Andalusite in contact-metamorphic pelitic rocks adjacent to intrusions.
- Andalusite in the deeper parts of alunite-kaolinite (acid-sulphate) alteration centres related to palaeo-geothermal systems in subaerial volcanic terranes.

Types of economic deposits

Economic deposits of sillimanite minerals can be classified in a number of ways. Most of them fall within three genetic groups (Table 3): metamorphogenic, epithermal and supergene. The first is the economically most important in relation to deposits worked solely for their contents of sillimanite minerals. The latter two types provide in most cases sillimanite minerals as by-products or special blended products which make only a subordinate contribution to the production statistics.

Mined deposits, as well as potentially economic deposits (see Fig. 1), are largely represented by podiform and stratiform sillmanite and kyanite deposits, together with contact-metamorphic andalusite deposits. The podiform type consists normally of massive high-grade ores, whereas the stratiform type comprises quartzite horizons with 20-50% of sillimanite minerals. These two types of deposits may occasionally occur together in the same area or even form transitional types. Although the schist-type mineralisation globally contains vast resources of sillimanite minerals, exploitation has, in most cases, foundered on high recovery costs or poor quality of the concentrates due to the commonly intimate intergrowth between gangue and sillimanite minerals. It is presently of minor economic importance and will not be discussed further.
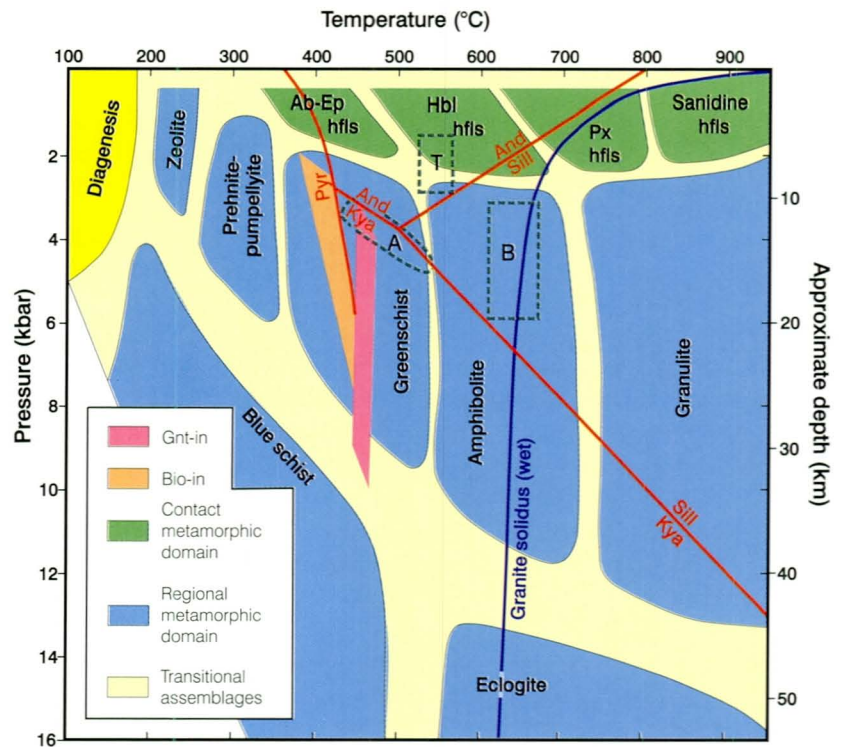
Economic sillimanite deposits

Podiform sillimanite deposits which are hosted by mica schists and gneisses comprise mainly irregular pods and lenticular masses of sillimanite-rich rocks with dimensions exceeding some hundred metres in length and several tens of metres in width, i.e. ore reserves rarely above 1 Mt. High-grade ores contain usually more than 80% sillimanite, which is intergrown with variable amounts of either corundum or quartz. Common subordinate constituents include rutile, Fe-Ti-oxides, topaz, tourmaline and dumortierite. They are usually mined as open pit operations and in tropical areas, by excavating and blasting large boulders (up to 100 tonnes) occurring buried in residual soils (laterites) and as float and landslide material. Massive sillimanite ores are often sold as coarse aggregates in pea- to lump-size grades which necessitate mainly crushing and classifying of the ores.

Table 3. Classification scheme for deposits of sillimanite minerals.

GENETIC TYPE OF DEPOSITS	GENETIC SUB-CLASS	GEOLOGICAL TERRANES	EXPLOITED MINERALS	EXAMPLES OF DEPOSITS	ASSUMED AGE OF FORMATION
Metamorphogenic	Regional-metam. Regional-metam. Contact-metam.	Metamorphic Metamorphic Plutonic	Sillimanite Kyanite Andalusite	Aggeneys distr.,South Africa Willis Mt., Virginia, USA Havercroft, South Africa Glomel, France	Palaeoproterozoic Palaeozoic Palaeoproterozoic Palaeozoic
Epithermal	Alunite-kaolinite	Volcanic	Corundum, andalusite and/or pyrophyllite	Semiz-Bugu district, Kazakhstan	Palaeozoic
Supergene	Beach sands Alluvial Eluvial/residual	All types All types All types in tropical/sub-tropical areas	Sillimanite Kyanite and sillimanite Kyanite Andalusite Sillimanite Kyanite	Kerala, India Trail Ridge, Florida, USA El Pino, NW Spain Transvaal, South Africa Khasi Hills, Assam, India Singhbhum, Bihar, India	Tertiary-Quaternary ' ' ' ' ' ' ' ' ' '

Fig. 3. Pressure/crustal depth and temperature diagram showing the position of different metamorphic facies (Yardley 1989) and the stability fields for andalusite, kyanite and sillimanite with the invariant point adapted from Holdaway (1971). The reaction curve for pyrophyllite (pyr.) = Al-silicate + 3 quartz + water (Kerrick 1968) represents the lower stability limit for andalusite and kyanite in the system Al_2O_3-SiO_2-H_2O. The lower stability for biotite (bio-in) and almandine garnet (gnt-in) in pelitic rocks is also shown for comparison. The wet granite solidus curve is taken from Luth et al. (1964). PT conditions for the formation of the Bushmanland sillimanite deposits (B), Transvaal andalusite deposits (T) and the Appalachian kyanite deposits (A) are according to mineral assemblages given by Joubert (1986), Miyano (1988) and Espenshade & Potter (1960), respectively.

The Bushmanland sillimanite deposits, South Africa

The deposits in the Aggeneys district of western South Africa were formerly a major producer of refractory-grade sillimanite. Production has decreased strongly over the last two decades due to exhaustion of high-grade reserves. They occur within the Namaqua Mobile Belt (Fig. 4) which represents a thrust-fold belt developed during the late Mesoproterozoic, as a consequence of accretion (Kibaran orogeny) along the southwestern margin of the Kaapvaal Craton (Thomas et al. 1994, Praekelt et al. 1997). In Bushmanland, the mobile belt comprises intensely deformed Palaeoproterozoic volcano-sedimentary sequences (2000-1650 Ma) intersected by different suites of mainly granitic plutonic rocks, and metamorphosed in the late Mesoproterozoic (see Fig. 3 for PT conditions) (Joubert 1986, Praekelt et al. 1997). Sillimanite deposits are hosted by sillimanite-biotite and quartz-muscovite schist units occurring interlayered with both mafic and acid metavolcanites of island arc-back arc affinities (Haib Sub-Group in Fig. 4; Colliston & Schoch 1996) and with dominantly meta-arenitic rocks (Aggeneys Sub-Group; Praekelt & Schoch 1997) assumed to represent shallow-water to fluvial deposits in a retroarc foreland-basin (Praekelt et al. 1997). The last setting is the most important in regard to economic sillimanite deposits, but also to stratiform exhalative base-metal deposits with associated bedded-baryte (Gamsberg, Black Mountain, etc.). The sillimanite deposits occur in the lower part of the Wortel Formation at the base of the Aggeneys Sub-Group and just above a basal transgressive arenite sequence resting on fine-grained granitic gneisses (Praekelt et al. 1997). They are interpreted as acid metavolcanites (Schreyer 1987). The deposits occur associated with lenses of amphibolites, calc-silicate rocks and locally dolomitic marbles as well as with different types of peraluminous rocks enriched in corundum, topaz, fluorite, tourmaline, gahnite, dumortierite, rutile, apatite, Al-phosphates, anthophyllite, cordierite, muscovite and/or sillimanite (Schreyer 1987, Willner et al. 1990).

The deposits occur associated with several kilometre-long trains of bodies forming conspicuous clusters of (quartz) sillimanite ores in the Hoston area (Frick & Coetzee 1974) and corundum-sillimanite ores in the Achab and Swartkoppies areas (Willner et al. 1990). In addition, topaz-rich sillimanite rocks may occur, as in the Achab deposit (de Jager & von Backström 1961). The individual bodies vary in size from a few decimetres wide and some metres long to nearly 100 m wide and 250 m long. The largest bodies had, prior to mining, estimated reserves in the range 200-250 000 tonnes (de Jager & von Backström 1961; de Jager 1963). The Swartkoppies deposit, which was recently worked (Fig. 5), consists of corundum-dominated ores containing 60-80% sillimanite and 40-20% corundum. They are locally enriched in magnetite and rutile and may grade into or be intersected by vein-like masses composed nearly entirely of sillimanite. The ores have a massive appearance and show colours in shades of pale blue and grey (de Jager & von Backström 1961). Their grain size is highly variable and frequently fine-grained fibrolite is found to replace coarse-grained needles and sheaves of sillimanite (Schreyer 1987).
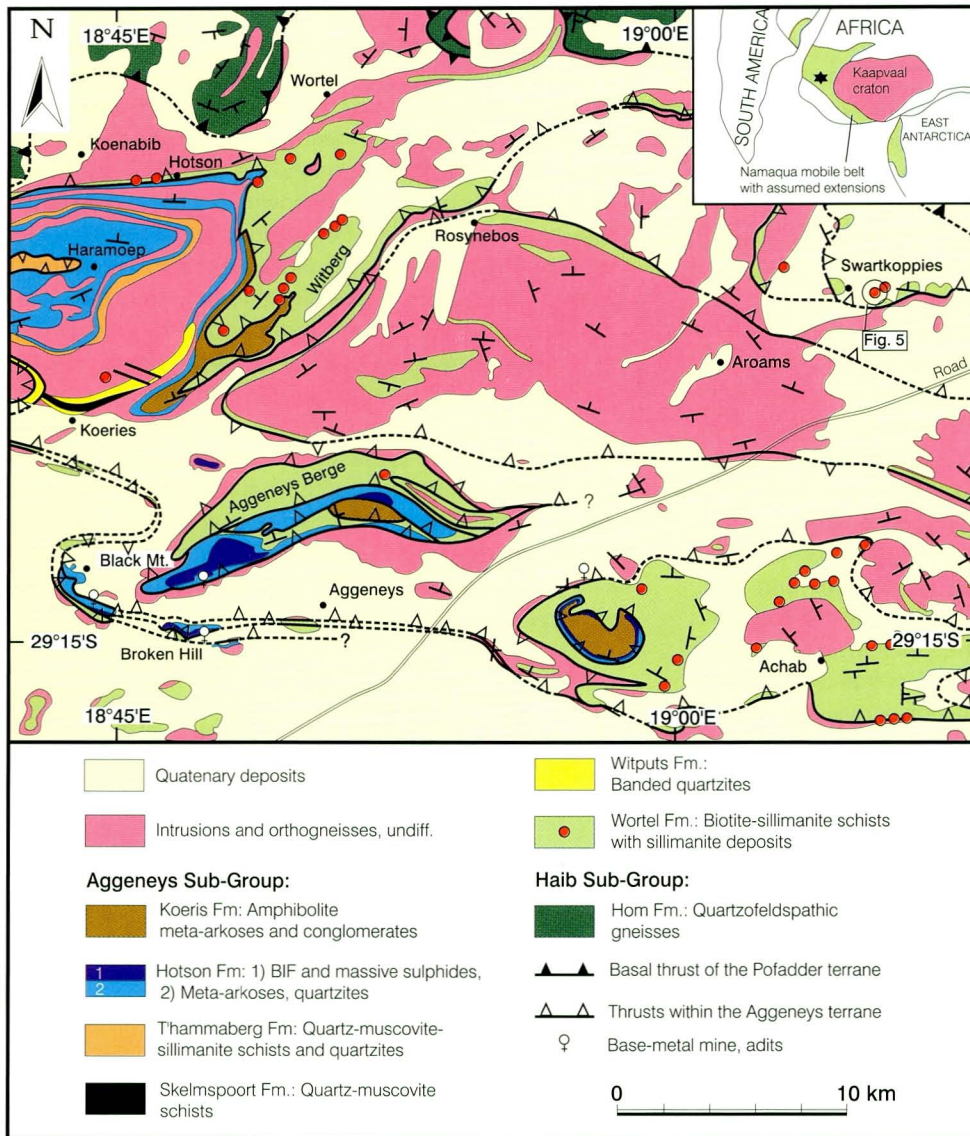
Fig. 4. Geological maps showing the setting of the Bushmanland silli-manite deposits. a) Location of the Namaqua Mobile Belt; simplified from Colliston et al. (1991) and b) geological map of the Aggeneys Terrane and its border zone with the Pofadder Terrane in Bushmanland showing the distribution of major lithostratigraphical units, thrust faults, base-metal ores and high-grade sillimanite ores. Simplified segment of Fig. 2 in Colliston et al. (1989) with the location of individual sillimanite deposits according to de Jager (1963), Frick & Coetzee (1974), Willner et al. (1990) and Praekelt & Schoch (1997). The deposit shown in Fig. 5 is marked by a circle.
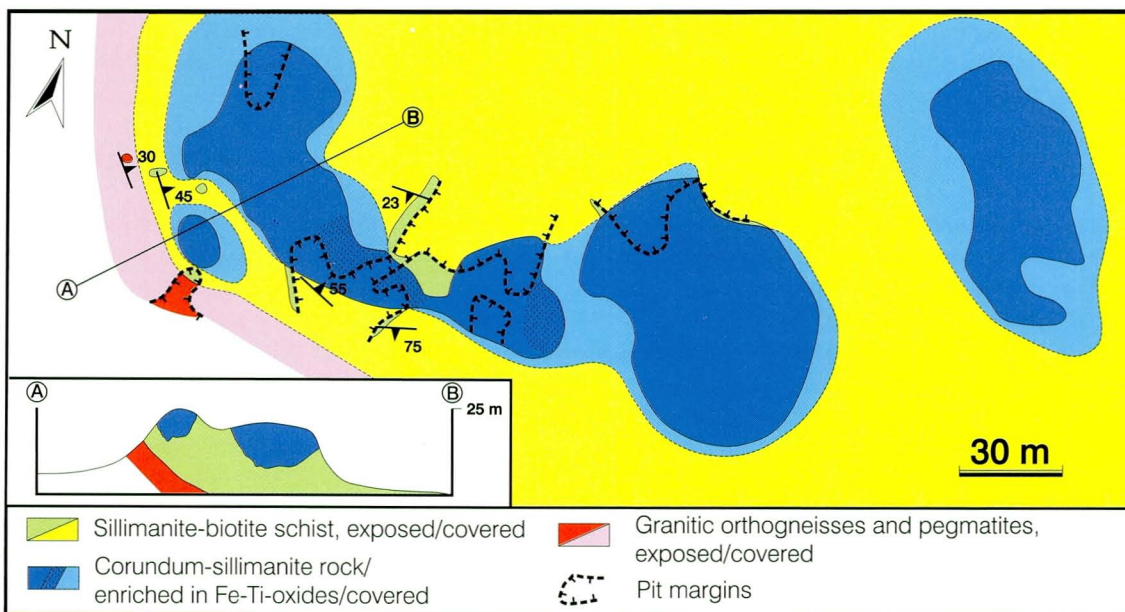

Fig. 5. Simplified geological map and section of the Swartkoppies corundum-sillimanite deposit, redrawn from de Jager & von Backström (1961).

Economic andalusite deposits

Andalusite is produced mainly from contact-metamorphic pelitic shales and schists occurring in the thermal aureole of both granitic and gabbroic plutons. Exploitable andalusite occurs as coarse-grained disseminated porphyroblasts constituting 5-20% of the host rock. The Glomel deposit in Brittany, France, is developed in Ordovician schists containing about 15% andalusite crystals (O'Driscoll 1999). It occurs in association with Hercynian granite massifs along the Armorican chain. Comparable granite-related deposits are also found in China (Lu 1998) and South Korea (Roskill 1990). However, the most important type are the contact deposits along the margin of the Bushveld Igneous Complex in South Africa where high-grade reserves and inferred resources are in the order of 50 Mt and 200 Mt, respectively (Oosterhuis 1998). The andalusite ores in both France and South Africa comprise weathered schists and hornfelses which facilitate both open-pit mining and subsequent dressing, which mainly include different types of heavy-media and high-intensity magnetic separation. Ore reserve calculations embrace mainly the upper weathered section rather than the andalusite-hornfels protore which suffers from higher beneficiation costs, smaller grain size and lower recovery.

Economic kyanite deposits

Medium- to high-grade ores of kyanite are more widespread than comparable sillimanite deposits (see Fig. 1). They can be subdivided into podiform and stratiform types (Table 3). The first type, representing high-grade (topaz-corundum)-kyanite ores, resembles strongly the podiform sillimanite deposits and has become well known from the mining of the Lapsa Buru deposits in the Singhbhum belt of the Bihar and West Bengal states of India (Banerji 1981). However, the most commonly encountered type is stratiform kyanite quartzites which form laterally extensive horizons or systems of lenses. The quartzites are composed of 20-50% kyanite, 80-50% quartz and subordinate amounts of muscovite, rutile, pyrite, topaz, dumortierite and tourmaline. The deposits are also characterised by the presence of various types of Al-phosphates, most commonly lazulite. Stratiform kyanite deposits with ore reserves often exceeding several million tonnes are normally worked as open-pit mines. The ores are crushed and milled prior to flotation of kyanite and high-intensity magnetic separation.

The Transvaal andalusite deposits, South Africa

The deposits are all situated within the thermal aureole of the Palaeoproterozoic Bushveld Igneous Complex (BIC) which intrudes the Transvaal Supergroup (2600-2100 Ma; Strauss & Beukes 1996). Mines are presently operating in the Lydenburg, Groot Marico and Thabazimbi districts (Fig. 6a). Andalusite is developed in weakly deformed meta-pelitic rocks of the Pretoria Group representing the uppermost succession of the Supergroup. The thermal effect of the magmas can be traced up to 55 km away from the exposed intrusive contacts and caused the zonal development of metamorphic mineral assemblages in the pelitic rocks, including an outer andalusite zone. This zone fluctuates in parallelism with the contact of the mafic intrusions of the BIC (Fig. 6a) and cuts across the sedimentary layering as in the Lydenburg district (Fig. 6b) (Hammerbeck 1986). In spite of considerable strike lengths of the andalusite zones, only certain pelitic units with optimum chemical composition and metamorphism (see Fig. 3 for PT conditions) have developed the right combination of high concentration of coarse-grained andalusite crystals, low contents of coarse-grained deleterious gangue minerals (garnet and staurolite) and appropriate amounts of sericitisation and softening of the rocks by weathering necessary for their exploitation. These conditions are mainly encountered in the pelitic members of the Timeball Hill Formation which carry potential andalusite hornfelses over strike lengths and widths exceeding 15 km and 20 m, respectively (Hammerbeck 1986; Oosterhuis 1998). The mined hornfelses contain normally 8-13% of coarse-grained andalusite with lengths and diameters in the range 10-50 mm and 1-4 mm, respectively. Staurolite and garnet present in the ores must have grain sizes in the lowest size-range of the andalusite crystals, whereby they can be removed by screening (Oosterhuis 1998).

The andalusite deposits in the *Lydenburg district* include both hard-rock and supergene deposits, the last one representing 1-2 m-thick alluvial accumulations with limited extent and containing 50- 80% andalusite. Weathered andalusite hornfels is the dominant ore type which is mined at Krugerspost, Annesley, Havercroft and Hoogenoeg, each producing annually about 50 000 tonnes of andalusite (Fig. 6b) (Oosterhuis 1998). *The Havercroft mine,* which was reopened in 1998 (O'Driscoll 1999), is situated in the upper part of the Timeball Hill Formation. The deposit comprises a c.50 m-thick and more than 5 km-long zone of banded, carbonaceous andalusite hornfelses dipping c.15° SW (Human & Collins 1986). The ore zone contains only subordinate barren layers and strongly retrograded units of sericite-rich hornfelses regarded as waste material. The lower 5 m of the ore zone is termed the Giant Crystal Zone due to the presence of megacrystic chiastolite with diameter and length of around 15 mm and 100 mm, respectively. This zone grades into normal hornfelses containing coarse-grained idioblasts of chiastolite (10 mm long). Most of the chiastolite is enveloped by a thin coating of sericite alteration. This coating permits the crystals to be separated cleanly from the hornfelses during crushing and mineral separation when the thin sericite layer is removed by attrition. The end product was a very coarse-grained and high-grade andalusite concentrate marketed as Grade1 Macle and Macle 60 (see Table 2).
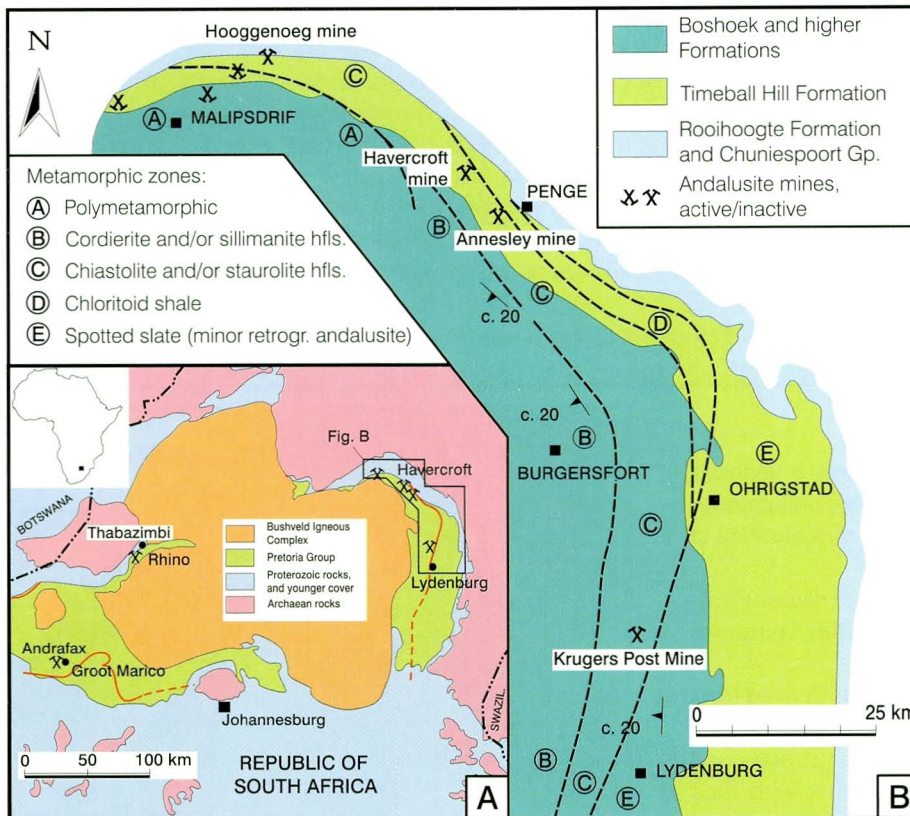
Fig. 6. a) Simplified geological map showing the distribution of major mining districts and andalusite mines in relation to the Bushveld Igneous Complex, the Pretoria Group and the outer boundary of the andalusite zone (red line). b) Map showing the distribution of andalusite mines and metamorphic zones in relation to the Timeball Hill Formation in the Lydenburg district, eastern Transvaal. Maps compiled from Anhaeusser & Viljoen (1986), Hammerbeck (1986) and Oosterhuis (1998).

Kyanite quartzites in the Appalachian belt, eastern USA

The Appalachian deposits of kyanite quartzites cluster in two main areas at the western margin of the Carolina Terrane (Fig. 7), respectively in the Charlotte Belt of Virginia and in the Kings Mountain Belt of North Carolina and South Carolina. Some additional examples are also found within the Carolina Slate Belt to the east. The Carolina Terrane comprises different segments of a mature Neoproterozoic-Cambrian island arc system (Secor et al. 1989). The Charlotte Belt, which constitutes a volcanic-plutonic complex, is thought to represent deeply eroded axial parts of the former arc system, whereas the supracrustals of the Carolina and East Slate Belts constitute overlying intra-arc and off-axis volcano-sedimentary sequences (Goldsmith et al. 1989, Feiss et al. 1993). The Kings Mountain Belt is comparable to parts of the Carolina Slate Belt, but at somewhat higher metamorphic grade. The timing of the medium-grade metamorphism responsible for the development of kyanite ores (see Fig. 3 for PT conditions) is poorly constrained and can be attributed to either Taconic or Acadian tectonothermal events (Drake et al. 1989, Osberg et al. 1989). The Carolina Terrane also carries different types of volcanogenic and exhalative deposits of base-metal sulphides, Fe-oxides, baryte and gold (Feiss & Slack 1989). Occurrences of economically important gold-pyrite and andalusite-pyrophyllite deposits with associated propylitic, silicic, argillic and advanced argillic alteration (high-alumina alteration centres) are conspicuous in the Carolina and East Slate Belts in conjunction with sub-marine to subaerial and intermediate to felsic volcanism (Schmidt 1985, Feiss et al. 1993).

The kyanite quartzites, according to descriptions given by Espenshade & Potter (1960), Conley & Marr (1980) and Horton (1989), form layers and lens-shaped bodies in intermediate to felsic metavolcanites and epiclastic to volcanoclastic metasedimentary rocks. The layers range in thickness from a few metres to more than 100 m and form laterally persistent stratigraphical units which can be followed continuously for several kilometres along strike. The individual horizons have become tectonically modified by tight to isoclinal folding and shearing. Towards their margins they become richer in muscovite and are commonly transformed into kyanite-muscovite-quartz schists. They may overlie or grade laterally into quartz conglomerates with a matrix composed of quartz, mica and kyanite. The quartzites contain kyanite as rather uniformally distributed crystals and lenticular aggregates with grain sizes normally in the range 3-30 mm. Almost monomineralic segregations of very coarse-grained and randomly oriented kyanite occur as scattered irregular pods, as thin envelopes on cross-cutting quartz veins and as ruler-shaped bodies along dilatational structures, locally truncating the gneissic fabric of the host-rock quartzite. The kyanite contents of the quartzites are normally in the range 10-40%. In addition, they contain usually less than 5% of rutile, muscovite, pyrite, magnetite, diaspore and topaz. Accessory minerals include various aluminous silicates and phosphates as well as spinel, tourmaline, corundum, barite, sphalerite and fuchsite. All of these minerals are also normally found in varying proportions in the high-alumina alteration zones in the Carolina and East Slate Belts.

The kyanite deposits at *Willis Mountain* and *East Ridge*, Virginia, which are presently mined, constitute two lens-shaped bodies containing several tens of millions of tonnes of open-pit ores with over 25% kyanite. According to Conley & Marr (1980), they occur in the core of two tight synforms (Fig. 8) and formed originally a single stratum unconformably overlying mafic to felsic metavolcanites of the Hatcher Complex which are possibly equivalent to the Cambrian Chopawamsic Formation (Pavlides et al. 1982). The kyanite quartzites rest on a thin basal sequence of quartz-mica schists with lenticular layers of micaceous quartzite and micaceous conglomerate. The kyanite ore bodies are composed of multiple wedge-shaped layers, each consisting of basal coarse-grained quartz-rich units grading upwards into kyanite-rich fine-grained quartzose rocks. Layers with relict cross-bedding and channel fill can locally be identified. Elsewhere in the area, this stratigraphic level carries bedded orthoquartzites which are overlain by a thick sequence of graphitic mica schists, correlated with the fossiliferous Arvonia Formation of Late Ordovician age (Drake et al. 1989).

Deposit models

The formation of andalusite deposits represents a textbook example of contact metamorphism of highly peraluminous pelitic rocks in relation to emplacement and crystallisation of gabbroic to granitic magmas.

The formation of the sillimanite and kyanite deposits is, in contrast, more poorly constrained and possibly comprises several different processes.

Metamorphism of high-alumina sediments derived from altered subaerial volcanites was advocated by Schreyer (1987) and Willner et al. (1990) to explain the stratabound and stratiform nature of the deposits together with their common affiliation with metapelitic units overlying sequences typified by felsic to intermediate volcanites. Based on the metamorphic minerals of the crude ores, the high-alumina sediments were interpreted to be composed mainly of variable amounts of quartz, diaspore, kaolinite and other alteration minerals. They were deposited in shallow-water basins adjacent to subaerial volcanic fields both coevally with the volcanism and during subsequent episodes of tectonic uplift. The differences between the protoliths of the podiform sillimanite and kyanite deposits in contrast to the stratiform kyanite quartzites can be related both to the amount of argillaceous alteration, silicification and hot-spring silica sinters in the source area and to mineral separation during transport and deposition. High-alumina clays, assumed to represent the protoliths of the podiform deposits, were probably deposited in a more offshore environment than the aluminous quartz sands of the stratiform deposits which locally grade into conglomerates.

Metamorphism of syn-volcanic and bedding-parallel quartz-kaolinite alteration of felsic tuffs has been advocated to represent the mechanism for the formation of kyanite quartzites intercalated with felsic volcanites in the Carolina Slate Belt (Bell et al. 1980, Schmidt 1985). The hydrothermal alteration zones were proposed to be situated below hot-spring and sea-floor exhalation centres and thereby be genetically linked to the development of local exhalite hori-
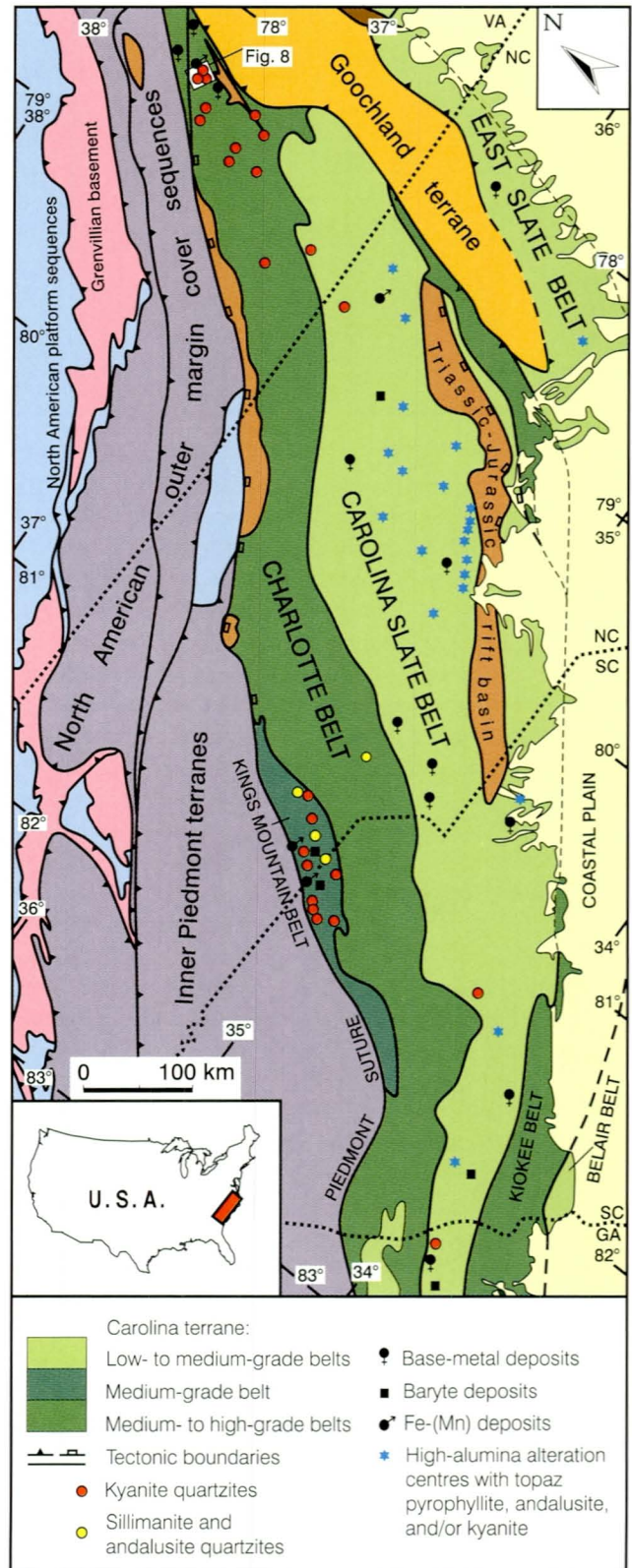
Fig. 7. Simplified geological map of the south-central part of the Appalachian orogen depicting the distribution of some important geotectonic units and terranes hosting kyanite and sillimanite quartzites, high-alumina alteration systems and stratiform Fe-(Mn), base-metal and barite deposits. The location of Fig. 8 is indicated. Map compiled from Espenshade & Potter (1960), Feiss (1982), Schmidt (1985), Horton (1989) and Hatcher et al. (1990).

Fig. 8. Simplified geological map showing the stratiform nature of the kyanite quartzite in the Willis Mountain area. Redrawn segment of Fig. 3 in Conley & Marr (1980) with additional data from Espenshade & Potter (1960) and Pavlides et al. (1982).
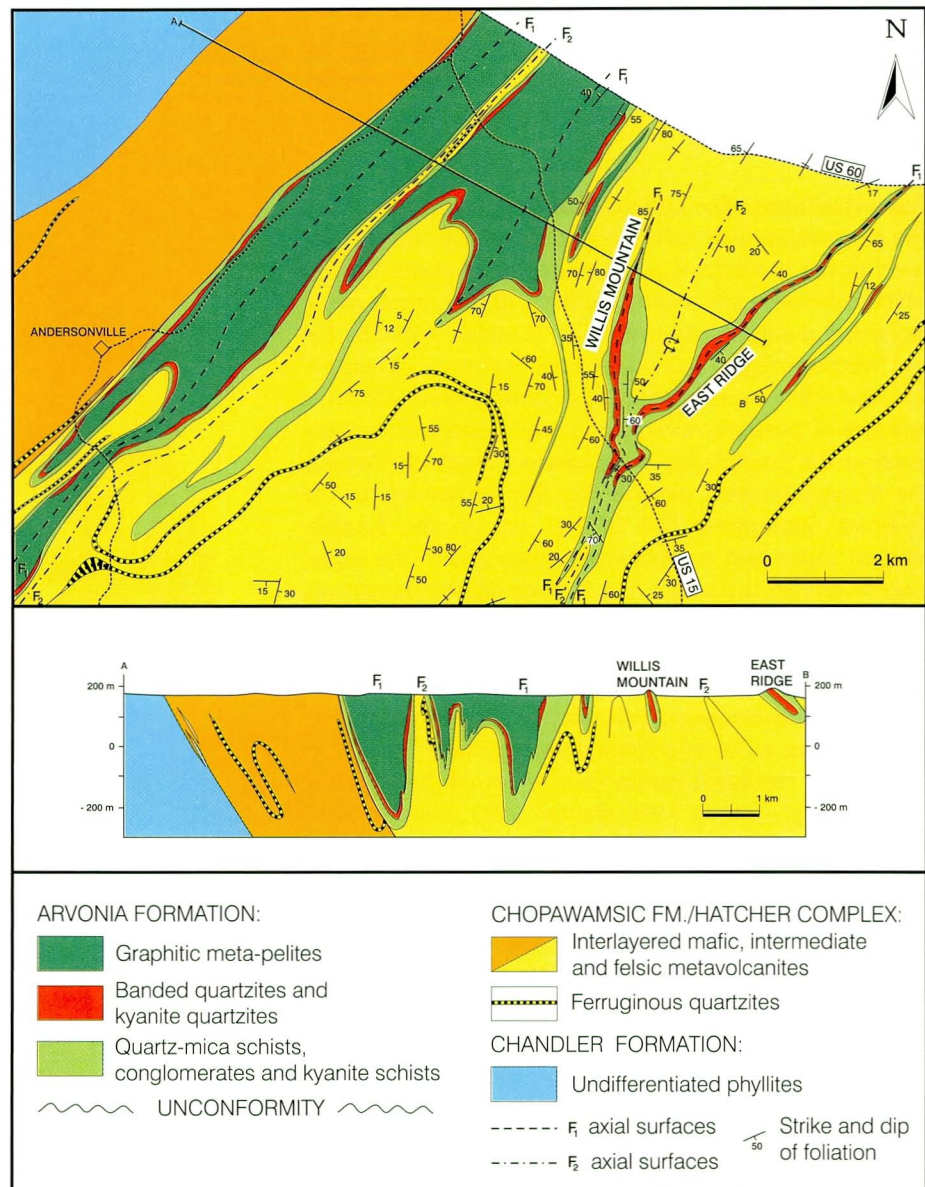
zons. Enhanced contents of fluorine, boron, barium, phosphorus, base-metals and sulphur in the quartzites are also common feature of most kyanite and sillimanite deposits and frequently also of their wall rocks. This can be ascribed to enrichment in conjunction with sub-seafloor hydrothermal alteration and associated exhalative processes as well as to subsequent erosion of alteration centres enriched in these elements.

Shear-induced and syn-metamorphic metasomatism of aluminous rocks has also been proposed to explain the frequent location of both types of deposits in close proximity to regional shear zones (Banerji 1981, Andréasson & Dallmeyer 1995, Ihlen & Marker 1998). Such models are supported by the invariable presence of syn-metamorphic, hydrothermal veins and segregations of kyanite and sillimanite in the deposits (Espenshade & Potter 1960, de Jager & von Backström 1961, Schreyer 1987, Lundegårdh 1995). Comparable but regional systems of syn-metamorphic upgrading of aluminous rocks are found in the eastern part of the Fennoscandian shield (Khizovaara; Roskill 1990). Laterally extensive gar-

netite zones (silicate-facies iron formations) are here intruded by tonalites and both are veined and pervasively replaced by staurolite, kyanite and quartz in conjunction with superposition of Palaeoproterozoic shear zones (Ihlen et al. 1994, Ihlen & Marker 1998).

Potential areas and occurrences in Norway

Norway is well-endowed with plutonic and medium- to high-grade metamorphic terranes containing lithologies and mineralisations, commonly found associated with economic sillimanite-mineral deposits. So far, exploration work has been conducted on deposits of mainly kyanite-rich mica schists (e.g. Sørøy) and some kyanite quartzites (e.g. Saltfjellet) in the Caledonides. The investigations have normally foundered on high recovery costs and/or mineral dressing problems. Thus, no deposits have been put into production. An attempt will be made below to point to some potential areas and occur-

rences which deserve attention as possible targets for exploration work. In this context it is important to emphasise that Norway is situated close to the world's leading refractory market in central Europe, thereby providing a competitive advantage.

Potential areas for sillimanite deposits

The most widespread occurrences of sillimanite are encountered in the Proterozoic paragneisses of southern Norway which have been affected by medium- to high-grade metamorphism during the Kongsbergian (Gothian; 1.75-1.55 Ga) and Sveconorwegian (1.2-1.0 Ga) tectonothermal events. Sillimanite-rich metasedimentary rocks interlayered with felsic gneisses of possible volcanic origin are especially encountered in the amphibolite-facies gneiss complexes flanking the Mesoproterozoic bimodal volcanic sequences of the Telemark Supergroup (1.0-1.5 Ma), e.g. in the Bamble-Modum sector and neighbouring areas, and in the Agder Gneiss Complex to the west (Fig. 9). According to mapping by the author, similar sillimanite-rich paragneisses with associated silicate-facies iron formations are also found in the Set-skog area, southeastern Norway, in conjunction with felsic metavolcanites. However, indications of podiform sillimanite deposits have so far only been detected inside the pelitic-arenaceous metasedimentary sequences of the *Bamble-Modum sector* (Jøsang 1966, Morton 1971, Starmer 1976, 1978). These are in many aspects similar to the sequences hosting the Bushmanland sillimanite deposits, and contain sillimanite-cordierite rocks in the Bamble area (Morton et al. 1970) and small bodies of massive sillimanite rocks, encountered by the author in the mica schists adjacent to the Skut-terud Co-As sulphide zone in the Modum area (Andersen & Grorud 1998). Admittedly, these bodies are far too small to attract any major attention, but may give indications of a suitable depositional environment for the necessary alumina-rich protoliths. Thus, the best starting point for exploration at the present state of knowledge would be in the Bamble-Modum sector.

Potential andalusite occurrences

Andalusite is found associated with plutonic complexes intruding low-grade metamorphic rocks in the *Caledonides* and in the *Oslo Igneous Province* (Fig. 9). The andalusite-cordierite hornfelses in the latter province are developed at the contact between Cambrian-Early Ordovician black shales (alum shales) and Permian granitic plutons (Brøgger 1882, Goldschmidt 1911). The andalusite zones in the *Eiker-Sands-vær area* are c.10 m thick and contain rarely more than c.7% of coarse-grained chiastolite crystals. They appear to be sub-economic.

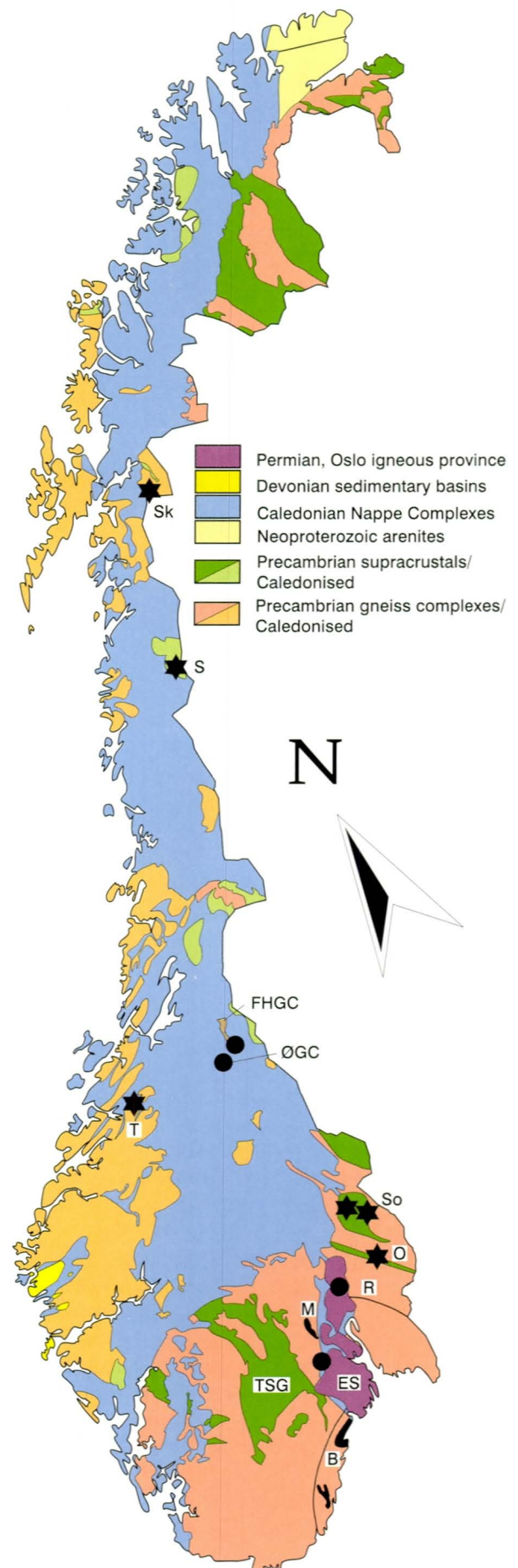The most prominant development of andalusite in Nor-

Fig. 9. Simplified geological map of Norway (Sigmond 1985) outlining the sillimanite-bearing argillaceous-arenaceous sequences (black) in the Bamble-Modum sector and known occurrences of andalusite schists and kyanite quartzites. Abbreviations: B = Bamble, ES = Eikern-Sandsvær, FHGC = Fongen-Hyllingen Gabbro Complex, M = Modum, O = Odal, R = Romeriksåsen, S = Saltfjellet, Sk = Skjomen, So = Solør, T = Tverrådalen, TSG = Telemark Supergroup and ØGC = Øyungen Gabbro Complex.

way is found in the contact-metamorphic aureole of the *Fongen-Hyllingen* and *Øyungen gabbro complexes* in the eastern part of the Trondheim Nappe Complex of the central Norwegian Caledonides (Birkeland & Nilsen 1972) (Fig. 9). The Fongen-Hyllingen gabbro complex, with a zircon U-Pb isotope age of 426+8/-2 Ma, i.e. Early Silurian (Wilson et al. 1983), was emplaced into the Early Ordovician Fundsjø Group (Wilson & Olesen 1975, Sturt et al. 1997). The Øyungen gabbro complex of unknown, but possibly comparable age (Wellings 1996) intrudes metapelitic rocks of the Åsli Formation (Bjerkegård & Bjørlykke 1994); now considered part of the Early Ordovician Sel Group which rests unconformably on the Gula Group (Sturt et al. 1995, 1997). Both formations were in a low-grade metamorphic state at the time of the emplacement of the gabbro complexes (Wilson & Olesen 1975, Wellings 1996). Development of andalusite in peraluminous schists has occurred at a distance of 1-3 km from the intrusive contacts (Nilsen 1971, Bøe 1972, Birkeland & Nilsen 1972).

The andalusite schists comprise fine-grained, brownish-grey mica schists with a characteristic knobby appearance on weathered surfaces due to the presence of abundant 5-18 mm-long and 2-8 mm-wide andalusite porphyroblasts (Vogt 1941, Birkeland & Nilsen 1972). The contents of andalusite are variable, though generally around 20% (Birkeland & Nilsen 1972). Andalusite is in some areas pseudomorphosed by kyanite and staurolite as well as by micaceous aggregates related to a Late Scandian tectonothermal overprint (Bøe 1972, Wellings 1996). The exact dimensions of the individual andalusite-bearing zones are uncertain, although Birkeland & Nilsen (1972) give indications of lengths and widths in the range 4-8 km and 200-400 m, respectively. Both the reported andalusite contents of the schists and their dimensions appear to be economically interesting and the area warrants follow-up work.

Potential kyanite occurrences

Kyanite quartzites occur at several places in Norway (Fig. 9) and especially inside tectonic windows of the Caledonides where they comprise, from north to south, the Skjomen deposits (A. Korneliussen, pers. comm. 1999), the Saltfjell deposits (Gjelle 1988) and the Tverrådalen deposit (J. E. Wanvik, pers. comm. 1999). The deposits in the Solør district of Southeast Norway are the only presently known ones outside the Caledonides (Nystuen 1969). All of these occur associated with Palaeoproterozoic felsic to intermediate volcanic sequences, related to the evolution of the Trans-Scandinavian Igneous Belt (TIB), evolving at the cessation of the Svecokarelian orogeny (Gorbatschev 1985). This belt, and possible correlative basement sequences along the western margin of the Caledonides in central and northern Norway, are therefore the best targets for kyanite exploration, although the explored deposits at Saltfjellet (Øines 1967) and in Solør (Jakobsen & Nielsen 1976, 1977) were regarded as sub-economic by industry.

The best potential for finding additional deposits is in the largely unexplored Solør district where four lens-shaped bodies up to 100-200 m wide and 2-3 km long are known to occur (Jakobsen & Nielsen 1976), interlayered with fine-grained grey and red biotite gneisses of the Kongsvinger Group (Gvein et al. 1974). The gneisses, interpreted as felsic metavolcanic and volcanoclastic rocks, can be correlated with the Östmark Formation hosting the former economic Hålsjöberget kyanite deposit in Sweden, which is assumed to predate gneissic TIB intrusions with an age of c.1.78 Ga (Welin & Kähr 1980, Lundegårdh 1995). The kyanite-grade metamorphism occurred during the Sveconorwegian orogeny (Page et al. 1996). Although the kyanite in the Solør district is generally fine-grained (average 0.5 mm), it is suitable for production of kyanite concentrates in the range 60-325 mesh, which is similar to that produced by Svenska Kyanite AB in the period 1985-1993 from the Hålsjöberget deposit (see Table 2; Anon. 1986). Though the known high-tonnage deposits are too low-grade (average ~18% kyanite) for exploitation, higher grade quartzites are possibly present, as indicated by the occurrence of an ice-transported block containing c.40% kyanite in the area north of Odal (Fig. 9) (Bryn 1962). If block-hunting is conducted, it should be noted that the transport distance for moraine blocks in the Solør district is within the range 2-7 km and is southerly directed (Jakobsen & Nielsen1976).

Conclusions

- Sillimanite minerals are mainly utilised in the production of mullite or high-alumina refractories. 95% of the world's consumption of these minerals is used for this purpose in the manufacture of metals, glass, ceramics and cement.
- The trade of sillimanite minerals occurs in an international market characterised by a few leading producers in South Africa (62% of total tonnage), USA (23%) and France (11%) and a high number of consumers in the refractory industry centred on the major iron and steel producing areas of the world such as the EU, the Far East and North America.
- Over-capacity in the refractory industry has led to intense competition for markets between different refractory raw materials.
- Cost-effectiveness and availability of the mineral products are more important than their unique physical and chemical properties. Local raw materials are thus often favoured, meaning that proximity to the market is a competitive advantage.
- For most purposes, the mineral concentrates should have alumina contents in the range 54-70% and be as low as possible in fluxing elements such as iron, titanium and alkalies contained in gangue minerals. Although coarse-grained mineral products are favoured, the present trend towards increased use of monolithic refractories allows increasingly finer size fractions to be marketed.
- The western world's production is dominated by andalusite with more than double the tonnage of kyanite, whereas sillimanite comprises only a small fraction of the total which reached 401 000 tonnes in 1998.

- Economic deposits of andalusite occur in the contact aureole of both gabbroic and granitic intrusions such as the Bushveld Igneous Complex in South Africa where the world's leading producers mine hornfelses with 5-20% of andalusite porphyroblasts.

- Economic deposits of sillimanite and kyanite are mainly found in metapelitic units occurring interlayered with or unconformably overlying felsic to intermediate metavolcanites. Such is the case of the massive podiform sillimanite deposits in the Bushmanland, South Africa, and kyanite quartzites in Virginia, USA. The pre-metamorphic and high-alumina sedimentary protoliths originally composed of variable mixtures of quartz, diaspore and kaolinite were deposited in shallow-water basins adjacent to subaerial volcanic fields with high-alumina alteration centres. The deposits are invariably affected by syn-metamorphic hydrothermal upgrading and some formed solely as a consequence of syn-metamorphic metasomatism of pre-existing peraluminous rocks in relation to shear-induced fluid migration in the deeper crust.

- All three types of metamorphogenic deposits are found in Norway. The andalusite schists in the contact-metamorphic aureoles of the Fongen-Hyllingen and Øyungen Gabbro Complexes in the Caledonides of central Norway are assessed to have the highest priority as follow-up targets. The known kyanite deposits occurring within the Transscandinavian Igneous Belt, are generally sub-economic, though there is still a potential for high-grade ores in the Solør district. There is potential area for podiform sillimanite deposits is the Bamble-Modum sector where small, massive, sillimanite bodies have been encountered in mixed metapelitic-arenaceous sequences comparable to those hosting the Bushmanland sillimanite deposits.

Acknowledgements

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