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Kaolin and halloysite deposits of Brazil

I. R. WILSON[1,]*, H. DE SOUZA SANTOS[2] AND P. DE SOUZA SANTOS[3]

[1] *Ian Wilson Consultancy, Withielgoose Farmhouse, Withiel, Bodmin, Cornwall PL30 5NW, UK,* [2] *Laboratorio de Microscopia Electronica, Instituto de Fisica da USP, Sao Paulo, Brazil, and* [3] *Laboratório de Matérias-Primas Particuladas e Sólidos Não-Metálicos, Dpto. de Engenharia Metalúrgica e de Materiais, Escola Politécnica da USP, São Paulo, Brazil*

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ABSTRACT: Brazil is a significant producer of kaolin with almost 2.5 Mt in 2005 representing 10% of the world's total of 25.0 Mt. Brazil is now the second largest producer in the world, after the USA, having overtaken the United Kingdom in 2005. The kaolin resources are widespread throughout the country and are varied in their origin, physical and chemical properties and morphology. The kaolin industry in Brazil has shown a dramatic rise over the last 15 years with production of beneficiated kaolin increasing from 0.66 Mt in 1990 to 2.5 Mt in 2005. The reason for the growth is solely the development of large kaolin deposits in the Amazon Basin that account for 90% of Brazil's production. In 2005 there are just two companies involved in the production and sales of kaolin from the Amazon Basin, namely Imerys (RCC – Rio Capim Caulim) and Caemi (a subsidiary of CVRD – Companhia Vale do Rio Doce) with kaolin operations of CADAM (Jari River) and PPSA (Capim River operations).

KEYWORDS: kaolinite, halloysite, Brazil, paper, clay, coating clay, ceramic.

Brazil is now a major producer of processed kaolin with an annual production estimated at almost 2.5 Mt in 2005 accounting for 10% of the world's production in that year. The growth of the Brazilian kaolin production has been at the expense of producers in the USA and UK whose market shares have been reduced (Wilson, 2005). The kaolin industry in Brazil has grown significantly from 0.66 Mt in 1990 to 2.5 Mt in 2005 (Fig. 1) due to the development of the Amazon sedimentary kaolin resources for paper coating. Of the 2.5 Mt production in Brazil, almost 90% is for export making Brazil the world's largest exporter of paper-coating kaolin. Ironically, as exports of coating kaolin have increased, the utilization of filler kaolin in Brazil has decreased significantly as paper mills now use precipitated calcium carbonate (PCC) as the primary paper filler. The estimated 0.3 Mt of kaolin produced in Brazil, excluding the Amazon deposits, are for a wide range of industries ranging from ceramics (sanitaryware and tableware), paint, rubber, fibreglass and other uses.

* E-mail: ian.r.wilson@btinternet.com
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DEPOSITS

Geologically, Brazil consists predominantly of a Precambrian basement of granites and migmatites associated with quartzites, gneisses and calcareous rocks of a similar age. These basement rocks are overlain inland in the south of Brazil by younger rocks ranging from Devonian to Cenozoic and the coast by the sedimentary Barreiras Formation and younger alluvials. The Brazilian basement is separated from the Guianan basement by the Amazon Basin that is occupied by sediments. The size of Brazil and the diversity of geology are reflected in the varying environments in which kaolinitic assemblages have been formed. In many parts of Brazil, kaolinitic clays often consist of a mixture of kaolinite and halloysite.

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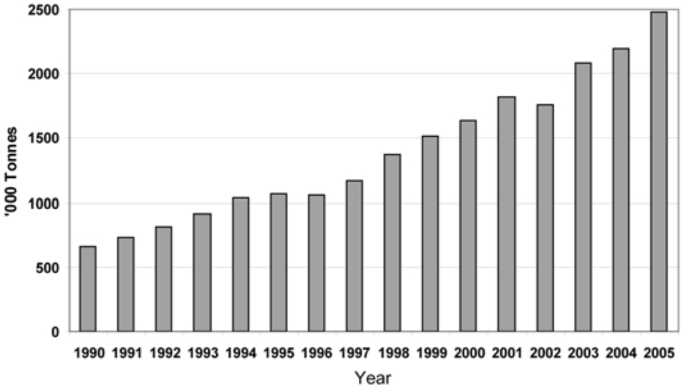

FIG. 1. Growth of kaolin production in Brazil, 1990–2005.

A classification of Brazilian kaolin deposits proposed by Souza Santos and Wilson (1995) is as follows: sedimentary kaolin; primary kaolin derived from pegmatites; primary kaolin derived from granitic rocks; primary kaolin derived from anorthosite; and primary kaolin derived from volcanic rocks.

The location of some of the Brazilian kaolin deposits is shown in Fig. 2. The most important commercial deposits in Brazil are of sedimentary kaolin from the Amazon Basin. Brazilian kaolin minerals exhibit varying morphologies with the sedimentary kaolin from the Amazon Basin being pseudo-hexagonal kaolinite of varying particle sizes with varying levels of Fe and titania, mainly located within the framework. Titania is also present in accessory minerals such as ilmenite, rutile and anatase. No tubular halloysite has been identified in the Amazon Basin sedimentary kaolin. There are also some sedimentary kaolin deposits being developed along the coastline near Recife (Pádua & Baraúna 1981).

Kaolins derived from pegmatites in the Minas Gerais area are a mixture of kaolinite and 7 Å/10 Å halloysite and can be very low in Fe and titania. Northeastern pegmatities contain predominantly euhedral kaolinite. Kaolin from granites generally has greater Fe contents than those from pegmatities and invariably comprises mixtures of kaolinite and 7 Å halloysite. Volcanic rocks produce fine siliceous kaolin that is often halloysitic whilst anorthosites are often a mixture of kaolinite and halloysite.

Some of the main operating companies for kaolin in Brazil are shown in Table 1 with brief details of their location, geology, production capacities and markets served (whether for paper, ceramics or other uses such as in paint, rubber and plastics). There is very little calcined clay produced in Brazil at the present time. Detailed reviews of the kaolin industry are prepared annually by the National Department of Mines (Kulaif, 2005).

It is the sedimentary kaolin deposits of the Amazon Basin with their natural high brightness, fine particle-size distribution, good rheology and low abrasion (absence of abrasive minerals such as quartz <~5 μm) which have become important sources of high-quality kaolin for coating paper. A detailed review of some of these and others deposits will now be considered.

DETAILS OF SOME DEPOSITS AND OPERATIONS

Sedimentary kaolin

The commercial development of the Amazon Basin kaolin commenced in the mid 1970s when Daniel Ludwig, the richest man in the world at the time, invested in the Jari River basin to produce pulp from local, fast-growing eucalyptus. During a search for phosphate minerals for fertilizers, sedimentary kaolin deposits were discovered. Daniel Ludwig developed the kaolin deposit until in 1982 the Brazilian Government took over the operations and instructed a consortium of Brazilian companies, including banks, to invest. Nowadays, the major investor in the Amazon Basin is Caemi, a subsidiary of Companhia Vale do Rio Doce (CVRD), a large mining company involved in exporting iron ore and other minerals. They now control a large number of kaolin deposits in the Jari

FIG. 2. Kaolin deposits of Brazil.

and Capim River areas of the Amazon Basin and are the largest producer of kaolin with their CADAM (0.9 Mt capacity plant) and PPSA (0.6 Mt capacity plant) operations based on the Jari and Capim river deposits, respectively. The largest single producer in the Amazon Basin is Imerys (the French Industrial Minerals Company which took over English China Clays (ECC) in 1999). They acquired the Rio Capim Caulim (RCC) operation from AKW and other partners and will produce up to 1.0 Mt in 2006. Other deposits, which have been extensively explored and evaluated, include Manaus in the heart of the Amazon region. The locations of the operating companies are shown in Fig. 3. The importance of the Amazon deposits as resources for paper coating has been highlighted by many authors (Pickering, 1994; Pickering & Linkous, 1997; Pickering & Murray, 1994; Harben & Virta, 1999, 2000; Crossley, 2001; Pruett & Pickering, 2006).

Rio Jari kaolin

CADAM is owned jointly by Caemi (61%), BNDES, a Development Bank (17%) and by the Bank of Brazil (22%). The kaolin deposit was

TABLE 1. Main operating kaolin companies in Brazil.

Company	Geology and resources (M tonnes)	Production capacities (all grades ktpa)	Main markets
Amazon Basin			
CADAM, Rio Jari, (Caemi Group, Brazil)	Sedimentary kaolin, 400 Mt	900	Paper 100%. Ultra-fine particle size
PPSA, Rio Capim (Caemi Group, Brazil)	Sedimentary kaolin lenses, 100 Mt	600	Paper 100%. Delaminated and blocky clays
RCC, Rio Capim, (Imerys Group, France)	Sedimentary kaolin lenses, 30 Mt	1000	Paper 100%. Delaminated and blocky clays
Mineração Horboy SA, Manaus	Kaolinitic sands, 76 Mt identified	–	No production. Good coating clay potential
Rio Capim Basin, (Caemi Group, Brazil)	12 deposits of kaolin Estimated 300 Mt	–	Resources available for future development
São Paulo State			
Mineração Horii Ltda, Jundiapeba, São Paulo	Kaolinized granites 10 Mt	120	Some paper filler, glass fibre and ceramics, paint
White Clay Tech, Embu Guaçu	Kaolinized pegmatite 1 Mt	–	Performance minerals, not yet operating
Mineração Romer Embu Guaçu	Kaolinized granite 1 Mt?	19	Filler clays, paint and ceramics
Sociedade Caolinita Embu Guaçu	Kaolinized granite 2 Mt?	24	Filler clays, paint and ceramics
Minas Gerais State			
Caolim Azzi, Mar de Espanha	Kaolinized pegmatites 2 Mt?	36	Filler clays
Empresa de Caulim Vermelho Novo	Kaolinized pegmatites 5 Mt?	60	Filler clays, paint, rubber, paper
Santa Catarina State			
Oxford Mineração Sao Bento do Sul	Kaolinized volcanics 5 Mt	68	Mainly for ceramics (porcelain/tableware)
Margil Mineração Urussanga	Kaolinized volcanics	18	Ceramics
Pernambuco State			
Industria de Caulim Junco do Seriodo	Kaolinized pegmatites	12	Filler clay, ceramics and paint

developed as a coating clay product for the paper industry (Almeida, 1987; Eisenlohr, 1980; Halward, *et al.*, 1977; Moeri *et al.*, 1987; Murray & Partridge, 1982; Pandolfo, 1979). The geology, genesis and origin of the Jari deposits have been described in detail (Kotschoubey *et al.*, 1999; Montes *et al.*, 2002; Souza Santos, 1975) with some bleaching processing trials carried out by Mesquita *et al.* (1996).

The kaolin deposit of the Felipe II mine has been operating for almost 30 y and is adjacent to the Jari River (Fig. 3). The sequence of 23 m overburden overlying 30 m of sedimentary kaolin (Fig. 4) with a small grit content is mined by scrapers and diggers. The kaolin matrix is first crushed dry and then made-down with water before undergoing degritting (by hydrocyclones). A new process recently introduced is selective flocculation where a small amount of polymer, which removes some of the particulate Fe and titania, is added. The resulting slurry is then pumped under the Rio Jari to the kaolin processing plant at Mungaba.

The Mungaba plant has a capacity of >1 Mt and has been operational since the late 1970s. The plant

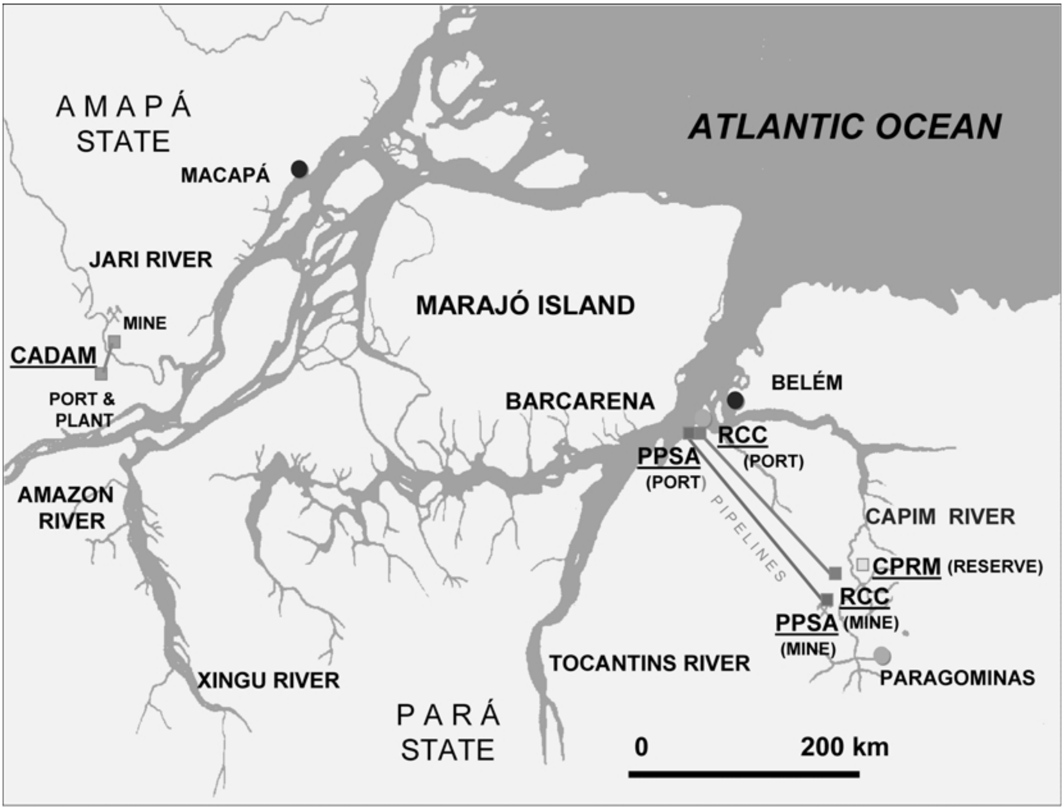

FIG. 3. Location of the CADAM, PPSA and RCC deposits and plants.

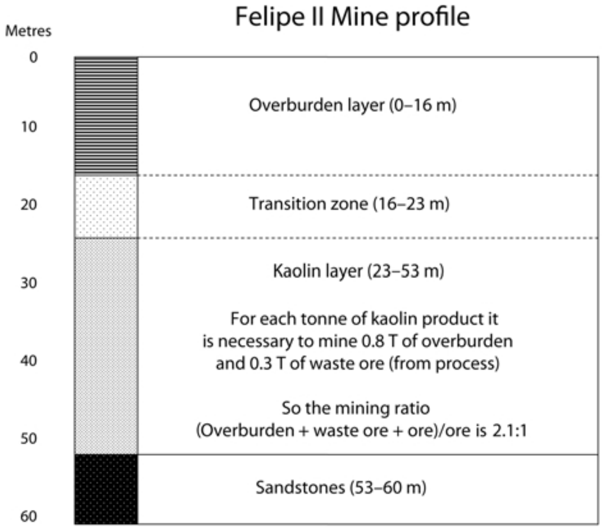

FIG. 4. Profile from the Felipe II CADAM deposit, Jari River.

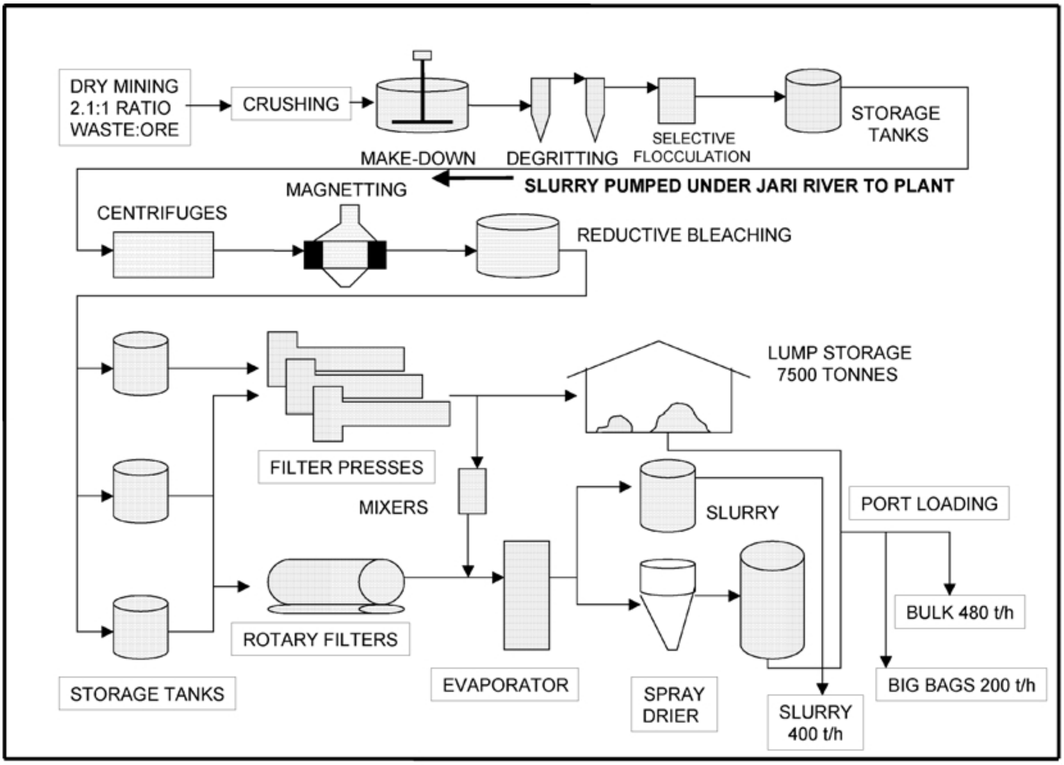

FIG. 5. CADAM flowsheet at Jari River operations.

has been expanded during this time with the introduction of new up-to-date centrifuges, high-intensity, wet-magnetic separators and rotary vacuum filters (to remove water and increase solids).

Details of the processing flowsheet are shown in Fig. 5. The Jari kaolin is characterized by very fine particle size and a typical SEM of the kaolin is shown in Fig. 6 along with a transmission electron microscopy (TEM) image of Amazon Premium in Fig. 7. The physical and chemical properties of Amazon Plus are shown in Table 2 and compared with the Century product from PPSA and a kaolin prospect from Manaus.

In 1999, products from CADAM were Amazon 88 and 90 (646 kt) and Amazon Premium (65 kt) making a total of 711 kt. From 1999 to 2001 the Amazon 88 and 90 products were phased out and replaced by Amazon Plus and Amazon Premium with a new product Amazon SB being introduced in 2002. The main characteristics of these three products are: (1) Amazon Plus – ultra-fine regular-brightness coating clay suitable for coating all paper and board, with good rheology and high glossing characteristics; suitable for blending with GCC (ground calcium carbonate) in topcoat; (2) Amazon Premium – ultra-fine coating clay suitable for CWF (coated woodfree) and CWC

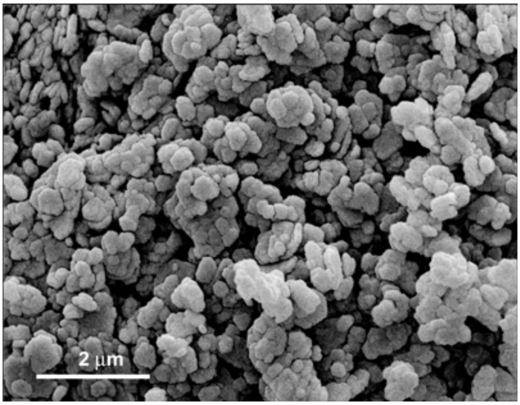

FIG. 6. SEM image of the Felipe II deposit kaolin – note the very fine particle size of the euhedral blocky kaolinite crystals (image courtesy of Caemi).

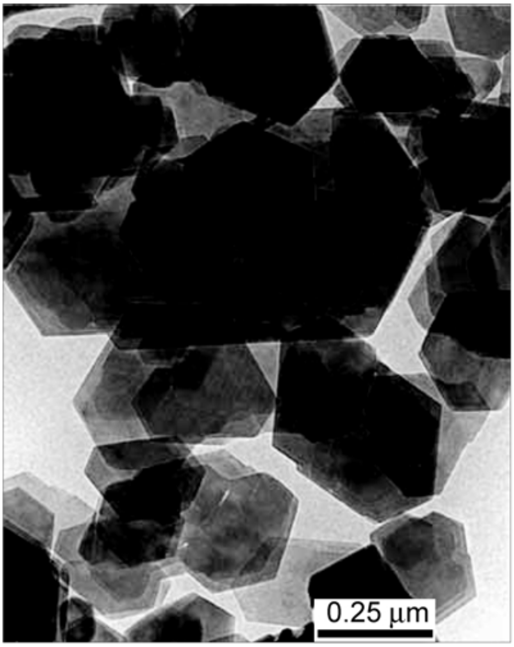

FIG. 7. TEM image of Amazon CADAM product showing the euhedral nature of the kaolinite particles down to 0.1 µm in size.

(coated wood-containing) papers and board, with good rheology, superior glossing and for blends with GCC; (3) Amazon SB – ultra-fine higher-brightness coating clay suitable for CWF application, with good glossing and rheology and suitable for blending with GCC.

The production and sales of CADAM products from 2000 to 2005 are shown in Table 3 and indicate little change during the 5 y period. In 2005, 10% of the sales were for domestic consumption and 90% for export.

Rio Capim kaolin

Both Caemi (PPSA) and Imerys (RCC) have mining operations in the Capim basin (Fig. 3) that have been developed to supply coating clay products to the paper industry. The geology of the kaolin deposits of the Capim basin, their origin and evolution, processing, stratigraphy and distribution are well documented (Hurst & Bósio, 1975; Kotschoubey *et al.*, 1996; Larroyd *et al.*, 2002; Barbosa, 2002; Santos & Rossetti, 2003, 2006; Nascimento & Góes, 2005).

Rio Capim kaolin – PPSA. PPSA is owned by Caemi (82%), IFC (4%) and Mitsubishi (14%). Quaternary sandy clays of the Barreiras Formation and Fe-stained sandstones overlie the kaolin deposits at Ipixuna. The first kaolin horizon is known as Hard Kaolin and is 10 m thick with fine particle size and low grit content (5%). An intermediate zone separates the hard kaolin from a soft kaolin zone of 5 m that has grit contents of 25% and brightness up to IS0 90. The full sequence is shown in Fig. 8. Up to a few years ago the underlying kaolinitic sands were not mined. However, a process has been installed to degrit the kaolinitic sand and a high-brightness material is

	Thickness (m)	PSD % <2 µm	Grit (%) >325 mesh	% ISO brightness
Quaternary Barreiras Formation Sedimentary sandy clays	12			
Iron-stained sandstones	8			
Erosion level – unconformity				
Tertiary Ipixuna Formation Hard kaolin	10	>80	5	70–80
Intermediate kaolin	1.5	>70–80	12	70–80
Mixed soft kaolin	5	50–70	25	72.5–90
Kaolinitic sand	8	50–70	>45	82-90

FIG. 8. Geological cross section of the Ipixuna kaolin deposit of PPSA, Capim River with details of particle size, grit levels and ISO brightness from the sequence.

TABLE 2. Comparison of kaolin qualities from three Amazon deposits.

Deposit	Jari River	Capim	Manaus
Name of mine	Felipe II	Ipixuna	Prospect
Company,	CADAM – Caemi,	PPSA – Caemi,	Min. Horboy Clays
Product name	Amazon Plus	Century	–
Capacity (Kt) 2005	900	600	No production
Sales (Kt) 2005	720	522	No sales
Reserves (Mt)	100	50	100
Type of deposit	Sedimentary	Sedimentary	Sedimentary
Geology	Lateritic profile	Kaolin lenses	Kaolinitic sand
Morphology	Pseudo-hexagonal	Pseudo-hexagonal	Pseudo-hexagonal
Product/Test result	Amazon Plus	Century	Coating clay
ISO brightness	87.5	88.8	89.0
ISO yellowness	5.2	4.7	5.3
Particle-size distribution (wt.%)			
>10 μm	0.1	0.02	0.01
<2 μm	98	81	94
<1 μm	95	61	84
<0.5 μm	80	33	59
<0.25 μm	46	10	14
<0.1 μm	10	–	–
Surface area	15	11	12
Viscosity concentration (%)*	74	73	75
Aspect ratio	9	14	–
Chemistry (wt.%)			
SiO_2	46.0	46.0	45.6
Al_2O_3	37.0	39.0	38.4
Fe_2O_3	1.8	0.62	0.91
TiO_2	1.0	0.77	0.57
CaO	0.06	0.01	<0.05
MgO	0.03	0.01	0.13
K_2O	<0.05	<0.05	<0.05
Na_2O	0.10	0.19	0.08
LOI	14.0	13.9	14.3
Mineralogy (wt.%)			
Kaolinite	100	100	100
Mica	–	–	–
Anatase/rutile	trace	–	–

* Viscosity concentration measured at 5 poise at 22ºC using a Brookfield Viscometer at 100 rpm.

being obtained. This clay is being evaluated by delamination to produce platy filler clays for high-brightness SCA (supercalendered A) paper markets as well as coating kaolin grades.

Strip mining is carried out by diggers and trucks deliver to a degritting stage. The kaolin is pumped a few kilometres to the main processing plant where a series of centrifuges separate the kaolin into coarse and fine particle-size fractions. Some of the coarse underflows are delaminated to produce platy kaolin. The fine-fraction kaolin undergoes magnetic separation (Carpco magnets at 5 T) followed by reductive bleaching. The resulting slurry is then passed through a vacuum filtration stage to increase the solids to 58%. This completes the processing of the kaolin that is then transferred to the port facilities

TABLE 3. Production and sales of kaolin from CADAM (2000–2005).

Year	Production (kt)	Sales (kt)
2000	721	740
2001	767	712
2002	711	719
2003	711	686
2004	750	745
2005	713	730

Source: Caemi

TABLE 4. Production and sales of kaolin from PPSA (2000–2005).

Year	Production (kt)	Sales (kt)
2000	314	318
2001	363	339
2002	330	337
2003	423	423
2004	460	463
2005	500	529

Source: Caemi

where it is prepared for shipment. The kaolin is dispersed (deflocculant added) and stored prior to pumping 180 km to the port of Barcarena (Fig. 3). At Barcarena the clay is screened and evaporated to increase the solids prior to drying in a large Spray Dryer. The moisture level is reduced to ~6% so that the product can be loaded by conveyors into adjacent vessels for shipment to Europe and elsewhere. Some kaolin is shipped in big bags (1 tonne), especially to markets in China. There is also a make-down facility so that slurry (at 70% solids) can be shipped to the USA tank farm in Maine where the product is delivered to local customers by road tanker. A summary of the flowsheet is shown in Fig. 9.

The Ipixuna kaolin deposit contains some naturally platy kaolin, especially from the hard kaolin horizon, as shown in the SEM in Fig. 10. The physical and chemical properties of the Century product are given in Table 2 and indicate a high brightness with good rheology.

The production and sales of PPSA kaolin are shown in Table 4 and show that from 2000 to 2003 the production and sales were much the same. However, with the introduction of a new product, Paraprint, sales are now increasing. In 2005 the

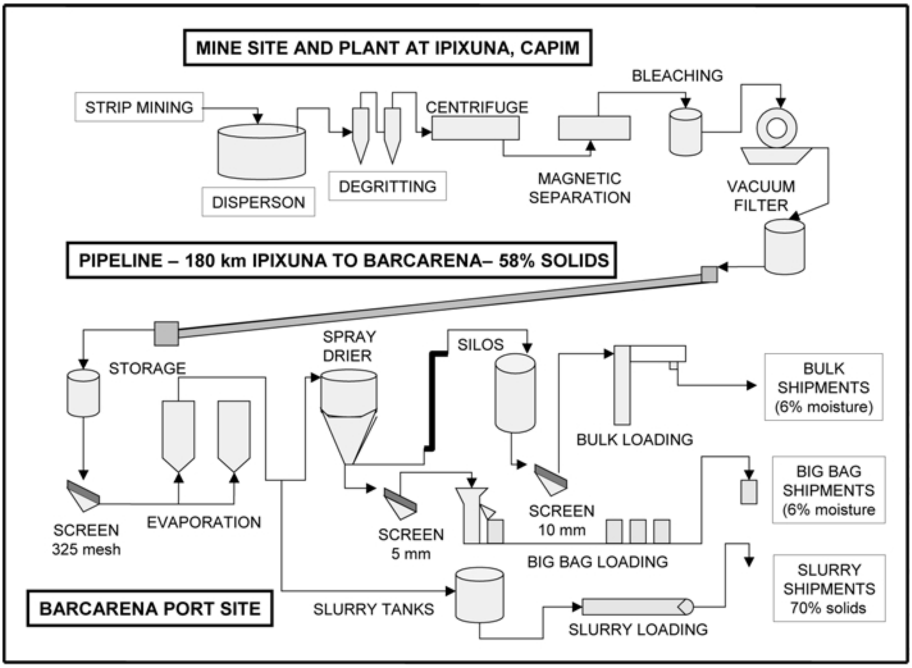

FIG. 9. Flowsheet of the Caemi PPSA mine, Ipixuna and Barcarena plants.

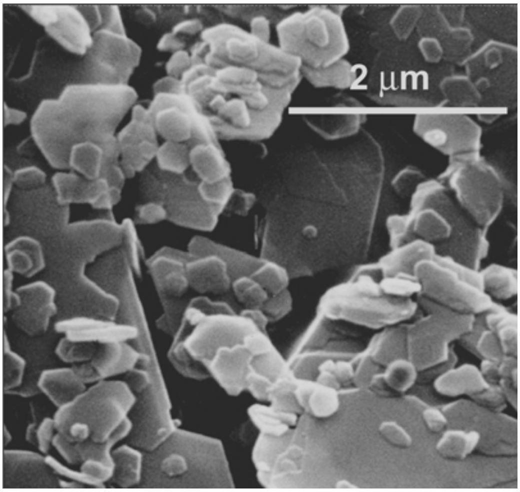

FIG. 10. SEM image of kaolin from Xpixuna deposit, PPSA, Capim River, showing the platy nature of the kaolinite (image courtesy of Caemi).

sales of kaolin were 529 kt of which 82% was Century and 18% Paraprint. Other new products, Paraplate and Paralux are being introduced in 2006. The range of products will be for paper coating as follows: (1) Century – a naturally delaminated, high-brightness, coating kaolin used in coated wood-free and coated wood-containing papers. The product has good optical properties and good printability; (2) Paraprint – a fine, naturally delaminated, high-brightness coating clay. Paraprint has a steep particle-size distribution and is particularly suited to imparting a good balance of opacity and gloss in a wide range of coated papers (CWF and CWC); (3) Paraplate – a naturally delaminated, extra platy, high-brightness coating kaolin with high aspect ratio, steep particle-size distribution combined with good rheology. It provides good coverage and optical properties and improved printability to fine coated papers (LWC – light-weight coated) and matt grades (CWF); (4) Paralux – a fine, naturally delaminated, high-brightness coating kaolin with steep particle-size distribution providing a good balance of opacity and gloss in a wide range of coated papers (CWF and CWC).

Now that CADAM and PPSA are both controlled by Caemi, the combined total sales for 2000–2005 with a projection for 2006–2010 is shown in Table 5. This indicates a steady growth from 1.26 Mt in 2005 to a projected 1.98 Mt in 2010, an increase of 57%. For the period 2000–2010 there is approximately a doubling of sales from 1.0 to 2.0 Mt. This growth is being driven by the introduction of new products to provide a range of particle size, brightness and performance for a wide range of coated papers. The relationship of particle size (fine and coarse) with brightness (regular and high) is shown in Fig. 11.

Rio Capim – Imerys Rio Capim Caulim SA

Imerys Rio Capim Caulim SA is now 100% owned by Imerys (Paper Group). When the mining company was first established, the kaolin ore was mined from the Rio Capim deposit and taken by barge to the processing plant built at Barcarena. This practice proved difficult at some times of the year especially when the river levels were low. Imerys followed the example set by PPSA and installed a 165 km pipeline from the deposit area to the plant at Barcarena. However, unlike PPSA where all the kaolin processing is carried out (apart from drying and bagging) in the mining area, the Imerys operation carries out de-sanding and some processing at the mine site and sends a semi-processed kaolin slurry down by the pipeline at ~40% solids. On arrival at the Barcarena plant the kaolin undergoes further refining and processing to produce the high-quality coating kaolin products such as Capim DG, NP and SP. The coarse reject material that is generated from the centrifuges is now being delaminated, and a new range of high-brightness platy filler clays are being produced for export. The current capacity of the plant is 850 ktpa

TABLE 5. Sales of Caemi products (CADAM and PPSA) for 2000–2005 and estimates for 2006–2010.

Year	Sales (kt)
2000	1058
2001	1051
2002	1056
2003	1109
2004	1208
2005	1259
2006	1444
2007	1590
2008	1721
2009	1836
2010	1978

Source: Caemi

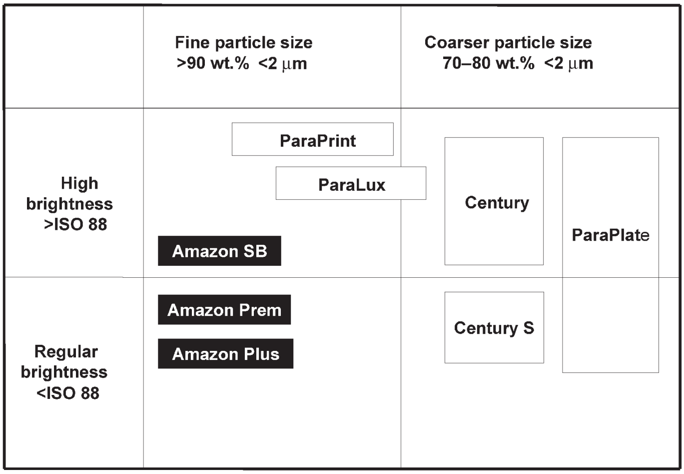

FIG. 11. Caemi – CADAM and PPSA products based on particle size and brightness.

for coating clays and 150 ktpa of filler clays, giving a total production capacity of 1.0 Mt. The coating clay products are of fine particle size and of high brightness as shown in Table 6.

The advantages that the Brazilian deposits have over other sources in the world (Pruett & Pickering, 2006) are: (1) they are superior kaolinite ores with low grit content and very pure kaolin of high brightness and whiteness, with favourable viscosity and paper-coating characteristics; (2) there is access to deep-water ship transport to worldwide customers; (3) there is low overburden ratio and relatively simple mining conditions; (4) there are abundant supplies of process water; (5) the labour costs are relatively low; and (6) there is a major nearby hydroelectric power supply in the case of the Capim area.

TABLE 6. Properties of Imerys Capim products – Capim DG and SP.

Product	Capim DG	Capim SP
ISO brightness	89.5	89.6
ISO yellowness	4.3	4.0
Particle-size distribution (wt.%)		
>10 µm	0.03	0.03
<2 µm	91	92
<1 µm	70	72
<0.5 µm	42	45
<0.25 µm	16	19
Viscosity concentration (%)*	74.6	72.2

* Viscosity concentration measured at 5 poise at 22ºC using a Brookfield Viscometer at 100 rpm.

Manaus kaolinitic sands

There are large sedimentary sequences of arkoses, kaolinitic mudstones and kaolinitic sands of the Alter do Chão Formation (Lower Tertiary/Cretaceous age) north of Manaus. The genesis, morphology and regional setting of the deposits have been described by several authors (Lucas, 1989; Vieira & Souza Santos, 2001; Costa & Moraes, 1998). The kaolin potential of the area was first realized in the early 1970s during road construction of the AM 10 and BR 174 roads. A typical sequence of lateritic soils with gibbsite and kaolinite is underlain by a mottled zone (pinkish stained) of kaolinite and Fe oxides. A pallid zone that is mainly of creamish-white to pinkish-whitish kaolinitic sands underlies this mottled zone. The kaolin sequences consist of low-defect kaolinite crystals. It was realized that the firmest base for the road going through the cuttings was hard kaolinitic sand. From 1972–74 ECC carried out studies in the area but no action was taken. In 1988 Mineração Horboy took up the exploration rights in the area and during 1989–91 ECC again carried out a detailed evaluation of the area with the objective of building a 300 ktpa plant. ECC identified >158 Mt of a standard coating clay product with an ISO brightness of >85, with excellent rheology. However, in 1991 ECC gave up their option on the deposit as they purchased The Georgia Kaolin Company from ABB in the USA. During 1994–1995 Rio Tinto Desenvolvimentos Minerais Ltda (part of Rio Tinto Group) had an option to explore the area. They carried out a detailed drilling programme and a detailed characterization study of the deposit. They identified 76 Mt of various high-quality products in selected areas of the deposit. These products included bright platy coarse kaolin suitable for precoat and matt offset paper, bright platy fine particle size kaolin suitable for blending with GCC in paper (Table 2) and platy kaolin for rotogravure applications. Rio Tinto withdrew from the project in 1995 when they made a decision to withdraw from the kaolin business with the closure of their Comalco operation in Weipa, Queensland, Australia.

Northeast sedimentary kaolin deposits

Small deposits of sedimentary kaolin, also with platy pseudo-hexagonal morphology, are exploited in the coastal belt along the south of Recife, Permambuco State (Fig. 2). The kaolin is used by the tableware and sanitaryware industries with calcined clay being used as a metakaolin in cement.

Kaolinized pegmatites

Brazil is well known worldwide for the large variety of semi-precious gem stones (tourmaline, beryl, amethyst, topaz and others) that are found associated with pegmatite deposits (Paiva, 1946). Many of the pegmatites consisted dominantly of K feldspar, quartz and mica with kaolin minerals formed from the subsequent alteration of the feldspar, and are found in the northeast and southeast (Minas Gerais) of the country (Fig. 2). The southeast pegmatite province of Minas Gerais is generally an assemblage of kaolinite and halloysite, with the northeastern pegmatities dominantly kaolinite (Campos & Souza Santos, 1986; Gopinath & Souza, 2000, 1990; Souza Santos *et al.*, 1964; Souza Santos, 1966; Souza Santos & Souza Santos, 1968, 1969; Souza Santos *et al.*, 1974; Souza Santos & Wilson, 1995; Wilson *et al.*, 1998).

Southeast pegmatite province

Some of the kaolinite-halloysite deposits in the province of Minas Gerais extend in a general SW–NE belt from Juiz de Fora in the south to Governador Valadares in the north (Fig. 12). The

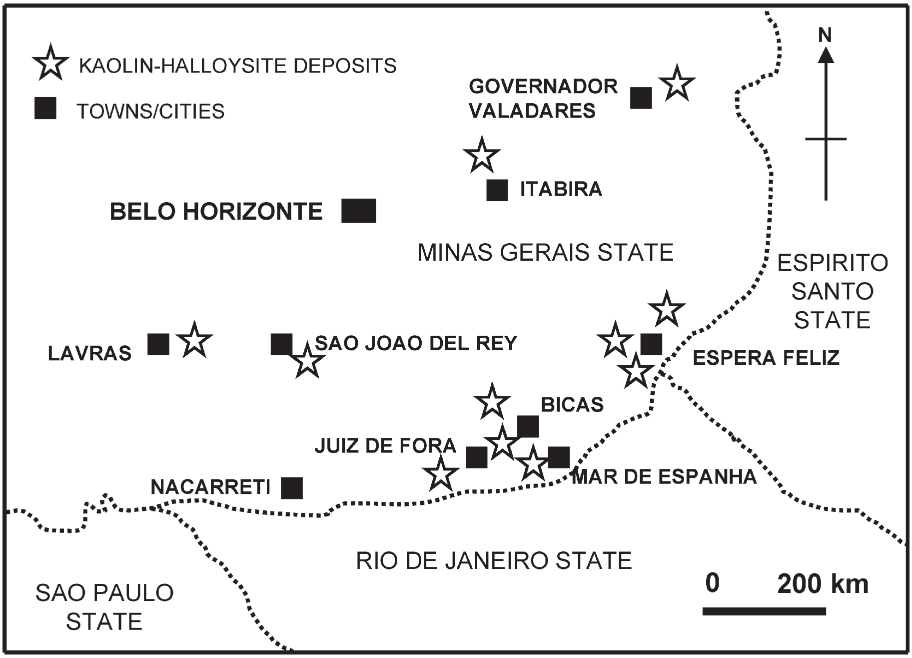

FIG. 12. Kaolin-halloysite deposits of Minas Gerais State, Brazil

nature of the deposits and their origin has been described by various workers (Pinheiro 2002; Ribeiro, 2003; Varajão *et al.*, 2001). Kaolin/halloysite is often associated with bauxite deposits in the region (Beissner *et al.*, 1997; Boulangé *et al.*, 1997; Oliveira & Toledo, 1997). The pegmatites, varying in width from 1 to 30 m, have been subjected to alteration by hypogene and subsequent supergene events, including weathering, and have produced a halloysitic-kaolinitic assemblage enclosing a central quartz leader. The typical clay assemblage from Minas Gerais pegmatites tend to be coarse in particle size with halloysite contents ranging from 10 to 70%. Detailed studies of Brazilian halloysite deposits have been carried out by many workers (Souza Santos & Souza Santos, 1969, 1968; Campos & Souza Santos, 1986; Kiyohara & Souza Santos, 1987) and these have been summarized by Souza Santos (1992, 1993). It is only possible to readily distinguish the tubular morphology of halloysite from the pseudo-hexagonal morphology of kaolinite by electron microscopy, since high-defect disordered kaolinite exhibits a similar X-ray powder diffraction pattern to halloysite (Brindley *et al.*, 1963; Souza Santos *et al.*, 1964). Details of the chemistry and physical properties of some clays from Minas Gerais are shown in Table 7. Chemically, these clays are low in Fe and titania and are of coarse particle size. The morphology of these clays is a mix of pseudo-hexagonal kaolinite and tubular halloysite as shown from a deposit near Mar de Espanha (Fig. 13). Some deposits, especially from the Mar de Espanha, Bicas, Pequeri, Linhares, Ibitiguaia, Governador Valadares, Caratinga, Carazul, Paraibuna and Cataguases districts have large percentages of tubular halloysite. Commercially, the kaolin-halloysite deposits were used to supply much of the paper filler and sanitaryware kaolin during the 1970s. However, much of this paper market was served with kaolin derived from kaolinized granite near Sao Paulo, and during the last 10 y has been replaced by precipitated calcium carbonate (PCC). The very low Fe and titania levels of these deposits make

TABLE 7. Physical and chemical properties of altered pegmatite deposits, Minas Gerais.

Deposit area	Minas Gerais		
Location	Governador Valadares	Bicas	Rio Preto
Name of mine	Marilac	Fazenda Avai	Nacareti
Morphology	Mix platy/tubular	Mix platy/tubular	Mix platy/tubular
% Yield (refined <15 μm)	25.0	43.3	12.9
Particle-size distribution (wt.%)			
>10 μm	23.1	11.0	20
<2 μm	24.1	30.4	30
ISO brightness	86.7	86.4	86.0
ISO yellowness	4.7	4.8	5.3
Chemistry (wt.%)			
SiO_2	46.0	46.0	45
Al_2O_3	40.0	39.0	40
Fe_2O_3	0.05	0.06	0.11
TiO_2	0.05	0.05	<0.05
CaO	0.04	0.03	0.03
MgO	0.03	0.08	0.03
K_2O	0.53	0.84	0.26
Na_2O	0.05	0.16	0.13
LOI	13.8	13.4	14.3
Mineralogy (wt.%)			
Kaolinite/halloysite	95	95	93
Mica	4	5	7
Gibbsite	trace	–	trace

FIG. 13. TEM image from a halloysite-kaolinite deposit, Mar de Espanha.

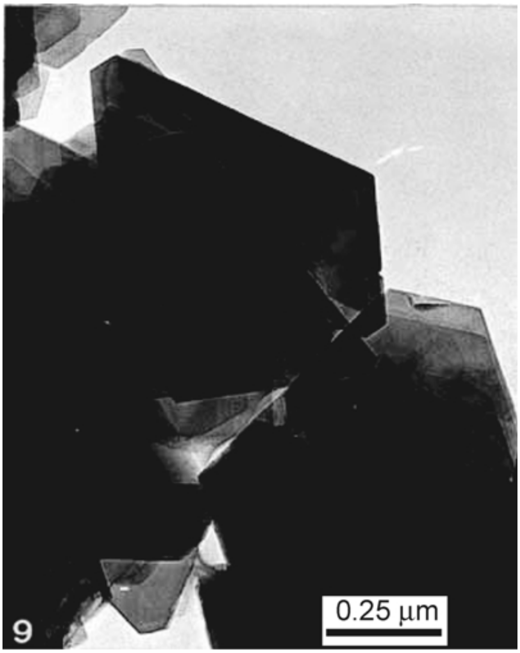

FIG. 14. TEM image of a kaolinite from Rio Grande do Norte.

them very suitable for use in porcelain and for other purposes such as extenders in paint and rubber. Some of the halloysite-kaolinite assemblages are calcined at low temperatures and the metakaolin sold to the cement and concrete industries. The deposits, however, are generally small in reserves and difficult to mine as very white, fully altered pegmatite is often adjacent to a very Fe-stained material which means that mining must be carried out by hand-picking. The largest kaolin producers in Minas Gerais are Caolim Azzi (Mar de Espanha) and Empresa de Caolim (Bela Vista). Kaolinitic-halloysitic assemblages are also exploited in the Petrópolis, Valença, Sapucaia, Araruama and Magé districts in Rio de Janeiro State.

Northeastern pegmatites

A concentration of pegmatites is found in Paraiba, west of Campina Grande in northeast Brazil (Fig. 2). Clay mined here is processed and sold to the paper, ceramic, paint and insecticide industries (Almeida, 1944; Ribeiro Filho, 1976; Roy *et al.*, 1964; Silva, 1973; Souza Santos *et al.*, 1974). These pegmatite deposits are different from the southeastern ones in that there is a complete absence of halloysite (tubular morphology). The occurrence of gibbsite in the southeastern pegmatites indicates some degree of leaching within a tropical weathering environment. The northeastern clays are always lamellar in morphology and finer in particle size and show signs of an earlier sericitic alteration phase that could be related to a hypogene event with weathering transforming the feldspars to kaolinite at a later stage. The morphology of kaolin from the Campinha Grande area is shown in Fig. 14. The circulation of groundwater and local chemical conditions could also have affected the observed pattern. Irrespective of origin, pegmatite-derived clays will continue to provide a source of material for various industries into the future.

Kaolinized granites

The known occurrences of kaolinized granite deposits are mainly in the southeast of Brazil, particularly in the Sao Paulo region. Generally, the kaolin deposits tend to be small and variable and are not mined to any great extent apart from in the Jundiapeba area east of Sao Paulo (Fig. 2). Clays derived by alteration of the basement granitic rocks (foliated Precambrian metamorphic migmatites, granites and gneisses) are generally tubular in morphology with a mixture of kaolinite/7 Å halloysite being common. The level of halloysite found is generally 50–70% except for the Jundiapeba region where kaolin is dominant (Fig. 15).

Empresa de Mineração Horii Ltda has mined the kaolinized granites of Jundiapeba since 1975. During the period 1981–2001, ECC do Brasil Mineração Ltda had a 20 y lease on part of the deposit and produced filler clay for the paper market. During this period Mineração Horii Ltda and ECC do Brasil achieved sales of up to 300 ktpa. However, in 2001, ECC do Brasil decided not to extend its lease on the deposit mainly due to the fact that sales of kaolin filler clay for paper were being replaced by precipitated calcium carbonate (PCC) produced in satellite plants. In 2006, Mineração Horii Ltda produces 120,000 tpa for many industries including fibreglass, a small amount for paper filler, ceramics, paint and other uses. In the Horii deposit the granite has been kaolinized to depths of 30–40 m. Morphologically, the clay is lamellar (kaolinite) often showing large stacks with only a small amount of halloysite, which makes this deposit unique in the São Paulo area (Souza Santos, 1993). For use in ceramic applications, the clay is coarse grained with poor strength and plasticity but with reasonable casting concentration and good casting rate. It is suitable for use in a sanitaryware body as long as it is mixed with finer plastic and higher-strength clays (Angeleri *et al.*, 1963; Amaraante *et al.*, 1981; Cardoso *et al.*, 1998; Wilson, 1998, 1995; Wilson & Souza Santos, 1982 (two references); Souza Santos, 1966). The filler clay formerly produced by ECC and Horii had an ISO brightness of 84–85 with typically 25 wt.% >10 μm and 25 wt.% <2 μm. This is coarse for filler clay but was very suitable for the local paper mills where it gained wide acceptance. The clay was sold in slurry form at 40 wt.% solids (flocculated) and also at 55 wt.% solids (deflocculated) delivered in road tankers to the papermills. Other kaolinized granites are encountered in the Embu Guaçu, Perus, Registro, Juquiá and Capão Bonito districts. The two largest producers today are Empresa de Mineração Horii Ltda and Sociedade Caolinita (Table 1).

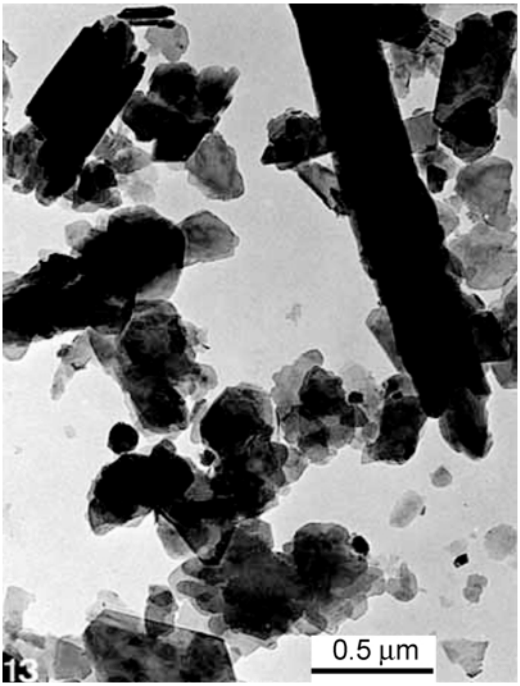

FIG. 15. TEM image of kaolinite with some halloysite from Jundiapeba, Mogi das Cruzes.

Kaolinized anorthosite

Kaolin derived from anorthosite is found west of Porto Alegre at Encruzilhada (Fig. 2). Geologically, the area consists of Precambrian migmatites, associated granites and the Capivarita anorthosite (Formoso, 1966). The anorthosite, a Ca-bearing feldspar, has been kaolinized and is presently being exploited by several companies who produce a wide range of materials for utilization in the rubber, paint, ceramics, insecticide and paper industries. There are many small mines that generally have a mixture of white and pink-stained clays that are mined selectively. Morphologically, the clay shows the presence of halloysite (tubes range from 1 to 3 μm and 7 Å halloysite type) and irregular platelets of kaolinite up to 2–3 μm in diameter, and often arranged in stacks.

Kaolinized volcanics

In the Sao Bento do Sul area (Fig. 2) in the northern part of Santa Catarina State there is the Serra do Mar mountain range consisting of Pre-Devonian sedimentary sequences overlying discordantly Precambrian migmatites and gneisses. The stratigraphy is complex but within the Pre-Devonian rocks are two types of volcanic rocks: acid volcanics consisting of rhyolites, ignimbrites, breccias and agglomerates; and, intermediate volcanics (andesite and dacites). The principal areas of kaolinization have been formed by the alteration of rhyolites and are mined by Ceramica Oxford in three locations – Turvo, Floresta and Kovalski mines. Descriptions of some of the mines and the physical and chemical characteristics of the clay have been presented by many authors (Biondi & Furtado 1999; Biondi *et al.*, 2000; Citrobi & Basci, 2001; Melchiades & Boschi, 2002; Toledo *et al.*, 2003, 2002).

In the Floresta mine the matrix is fairly soft and is dug out by a special framework shovel similar to a tubal from which the term ball clay was derived. The Turvo and Floresta mines are altered rhyolites with the Kovalski mine showing distinct flow banding typical of an ignimbrite. The chemical, physical and some ceramic properties of the three deposits are shown in Table 8. The Floresta mine material is a clay with reasonable strength and with a good fired brightness. The casting concentration is also suitable for use in tableware. In comparison, the Turvo clay is a low-strength ceramic kaolin with a good fired colour. The Kovalski clay is very similar to the Floresta clay but with a lower strength. Morphologically, the Kovalski clay shows a mixture of kaolinite stacks and halloysite, with the size of the tubes varying in length from 0.5

TABLE 8. Physical and chemical results of kaolinized volcanics, Sao Bento do Sul.

Deposit	Turvo	Floresta	Kovalski
Morphology	Mix tubular/platy	Mix tubular/platy	Mix tubular/platy
% Yield from matrix	39.3	41.7	37.9
Particle-size distribution (wt.%)			
>10 μm	10.9	10.5	7.8
<2 μm	37.7	48.3	55.2
ISO brightness	82.6	70.4	82.7
ISO yellowness	5.8	10.5	6.5
Ceramic properties			
Modulus of rupture (kgf cm^2 at 80% relative humidity)	4.6	12.7	7.8
Casting concentration (%)	57.3	62.5	63.6
Fired trials to 1180ºC			
Fired brightness	91.6	94.1	90.9
% absorption	18.1	20.6	21.3
% contraction	10.0	8.5	7.6
Chemistry (wt.%)			
SiO_2	49	53	57
Al_2O_3	36	33	30
Fe_2O_3	0.39	0.28	0.98
TiO_2	0.65	0.31	0.25
CaO	0.06	0.04	0.05
MgO	0.26	0.13	0.26
K_2O	0.43	0.05	1.20
Na_2O	0.10	0.10	0.06
LOI	13.1	13.5	11.1
Mineralogy (wt.%)			
Kaolinite/halloysite	93	91	89
Mica	–	–	–
Quartz	7	9	11
Anatase	trace	–	–

to 5.0 μm. Clay from all three of the deposits is used in a tableware body formulation in the local ceramic factory, Ceramica Oxford, with Floresta kaolin accounting for 45% of the body. The remaining 55% of the porcelain body includes Turvo sand (3%), Turvo kaolin (20%), Kovalski kaolin (12%), Sao Simao ball clay (6%), quartz (7%), talc (4%), bentonite (1%) and calcite (2%). The kaolin deposits are not suitable for use in paper production due to the high level of fine quartz that makes the products too abrasive.

FUTURE DEVELOPMENTS

At present, Brazil accounts for 10% of the world's production of kaolin based mainly on three operations in the Amazon Basin with a currently combined capacity of 2.5 Mt. The 2005 sales level from the three Amazon companies is of the order of 2.1 Mt. Projections for Caemi (PPSA Capim and CADAM Jari operation) are that sales for 2005 of 1.4 Mt will increase by 57% to reach almost 2.0 Mt by 2010. Allowing for a projected increase of 50% in the Imerys operation to 1.5 Mt will bring the combined capacities to a total of 3.5 Mt in 2010. It is expected that another Brazilian operation of 0.5 Mt, whether additional capacity additions from current producers, or another newcomer, will give a total of 4.0 Mt paper grade capacity by 2010. It is not anticipated that the local markets will increase significantly. Perhaps the current 0.36 Mt kaolin production in 2005 will increase to 0.5 Mt by 2010. This will give a projected total of 4.5 Mt of kaolin production in 2010. Current kaolin production in the world is 25 Mt. It is estimated that overall the world kaolin market will grow by 1.5% per annum between 2006 and 2010 reaching a projected 27 Mt global kaolin market in 2010. This would give Brazil (4.5 Mt capacity) a 17% share of the market, which is a significant increase over the current 10% global market position. Brazil is already the number one exporter of paper coating kaolin in the world and this position is expected to strengthen over the next 5 y. The increase in kaolin exports from Brazil will replace some of the markets supplied by the US which is still the number one kaolin producer in the world with approximately 8.0 Mt production capacity, slightly down from a level of 10 Mt ten years ago. Exports from Brazil at present are mainly to Europe and the Far East. However, exports to the USA, currently standing at 0.2 Mt in 2005, are expected to increase significantly. China remains a major target for all producers of high-quality coating kaolin and Brazil will be striving to increase its current exports to that country. However, the strengthening of the Brazilian real and weakness of the US dollar could have an adverse affect on exports from Brazil.

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