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A PRELIMINARY ASSESMENT OF KAOLIN FROM BODDINGTON GOLD MINE

B. Singh and R.R. Anand

CRC LEME OPEN FILE REPORT 186

March 2005

(CRC LEME Report 131R / CSIRO Exploration and Mining Report 705R,
2nd Impression 2005.)

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A PRELIMINARY ASSESSMENT OF KAOLINS FROM BODDINGTON GOLD MINE

Balbir Singh and R. R. Anand

CRC LEME Restricted Report 131 / E&M Report 705C

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EXECUTIVE SUMMARY

Kaolin has a wide range of commercial applications as a pigment, coater, filler, extender, raw material for ceramics, source of Al and Si, catalyst base, electrical insulator and as an inert base in pharmaceuticals. Some of the most common uses include paper coating and filling, and as a raw material for porcelain and dinnerware. Although kaolin occurs widely, only those deposits that have critical optical properties, purity, and proximity to infrastructure can be exploited commercially.

Boddington Gold Mine (BGM) processes large volumes of kaolin in extracting gold from the weathered zone. A field examination of the white patches on the pit walls suggests BGM kaolins to be of good industrial quality. Proximity to a port, minimal exploration, mining and processing costs add to the feasibility of kaolin mining at BGM.

The aim of this preliminary study was to test a limited number of BGM kaolins for a few of the most critical characteristics to make an initial assessment of their industrial value. Five samples were taken from various pit faces of BGM. The samples were analysed for their kaolin content, mineralogical purity, brightness, and morphology.

The following conclusions are made from the study:

- The BGM samples contain 50-70% kaolin, most of which (70-90%) can be separated into a <5 μm fraction. The kaolin content is better than many commercial kaolin deposits.

- There are minimal Fe- and Ti-oxides impurities in the <5 μm fraction of most samples. Most of the quartz is coarser than 5 μm and can be separated by a low-cost sedimentation process.

- The brightness of untreated BGM kaolins is comparable with the brightness of operating kaolin deposits, and is acceptable for use in ceramics and as a filler in paper, paint, and plastics without beneficiation.

- A paper coating-grade product may be produced from BGM kaolins using appropriate beneficiation processes common in the kaolin industry.

- The brightness of calcined BGM kaolins is remarkably high, and matches that of calcined products of beneficiated kaolins from other deposits. It is expected that calcination of BGM kaolins, after appropriate beneficiation, would result in exceptionally high brightnesses.

- Both halloysite and kaolinite-type kaolins can be produced from the BGM deposit.

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1.0 INTRODUCTION

Kaolin is a major industrial mineral that has a wide range of commercial applications. It is used extensively as a filler, coater, extender, raw material for ceramics, source of Al and Si, catalyst base, electrical insulator and as an inert base in pharmaceuticals. Suitability of kaolin for these various applications relate to its physical, optical, chemical and mineralogical properties. Although kaolin occurs widely, only those deposits that have critical optical properties, purity, and proximity to infrastructure can be commercially exploited.

Boddington Gold Mine processes large volumes of kaolin to extract gold from the weathered zone over the mineralization. A field examination of the bright-white patches on the pit walls suggests BGM kaolins to be of good industrial quality. Proximity to the port, minimal exploration, mining and processing costs add to the feasibility of kaolin mining at BGM.

The aim of this preliminary study was to test a limited number of BGM kaolins for a few critical characteristics to make an initial assessment of their industrial value.

The term kaolin is used here to include both kaolinite and halloysite. The two polytypes of kaolin generally occur in close association and have a similar chemical composition and structure. Kaolinite has a platy morphology whereas halloysite is generally tubular.

2.0 SAMPLING AND METHODS

Five samples were collected from various pit faces during the field visit (Table 1). A portion of the field sample was retained for reference and scanning electron microscopy (SEM) of the undisturbed surfaces. The rest was dispersed in water and passed through a 75 µm sieve to remove coarse quartz and iron mottles. The suspension of coarse fraction was sedimented, and clear water decanted before drying the sample at 80°C. The clay suspension flocculated without addition of any flocculant.

Particle size distribution of the <75 µm fraction was measured by laser scattering in a flow through cell using a Malvern Mastersizer E instrument. Next, a portion of the <75 µm fraction was suspended in deionised water and a few drops of 1M NaOH solution were added to disperse the clay. The <5 µm size fraction was separated from the suspension by sedimentation to remove fine quartz. The suspension containing the <5µm fraction was flocculated by adding a few drops of 1M $CaCl_2$. Clear water was decanted before drying the material at 80°C. The <75 µm fraction is referred to herein as coarse fraction and the <5µm fraction as the fine fraction.

Table 1. Sample number and location of the kaolin samples.

Sample No.	Location	Remarks
BGM-1	Pit B3, South East	White clay on the pit face
BGM-2	Pit B3, South East	Reddish purple clay
BGM-3	Pit E3, West	5 m below natural surface
BGM-4	Pit G, North	Drill spoil material
BGM-5	Pit D5	White clay on the pit face

The dry coarse and fine fractions were analysed for chemical composition by X-ray fluorescence (XRF) after fusion with Li-borate and mineralogy by X-ray diffraction (XRD) of the powdered sample.

Undisturbed sample surfaces were examined by SEM. Detailed information on particle size, shape, and kaolinite/halloysite ratios in the kaolin concentrates were obtained by investigating the fine fraction under high resolution SEM. Dry clay powder was deposited on a conductive tape and lightly coated with carbon before SEM examination.

The brightness was measured on both unfired and fired discs of clay. For each sample, one disc was prepared from a powder of fine clay. The disc was air dried overnight and then dried at 105°C for one hour. Unfired brightness was measured at a wavelength of 457 nm using a Elrepho 3000 reflectance meter, and expressed in ISO (International Standards Organisation) units. The disc was then fired to 1200°C and the brightness re-measured on the same instrument.

There are two main systems for measuring brightness: the ISO system, used in Europe, and the TAPPI (Technical Association of the Pulp and Paper Industry) or GE system used in the United States (Pickering and Murray, 1994). ISO brightnesses are about 1-2 units lesser than the GE brightnesses (Bristow, 1987).

3.0 RESULTS

3.1 Particle size analysis

The proportions of the >75, 5-75 and <5 μm fractions in the bulk sample are shown in Figure 1. Samples BGM-3, BGM-4 and BGM-5 contain about half the material in the <5μm fraction. BGM-2 contains the least amount in the fine and BGM-3 the most in the <5 μm fractions. BGM-2 has a significant amount of Fe oxides, which appears to affect dispersion of the clay.

Particle size analysis, carried out by laser scattering, shows a bimodal distribution. One population is centred at about 4 μm and other at about 20 μm. The latter population is probably dominated by quartz.

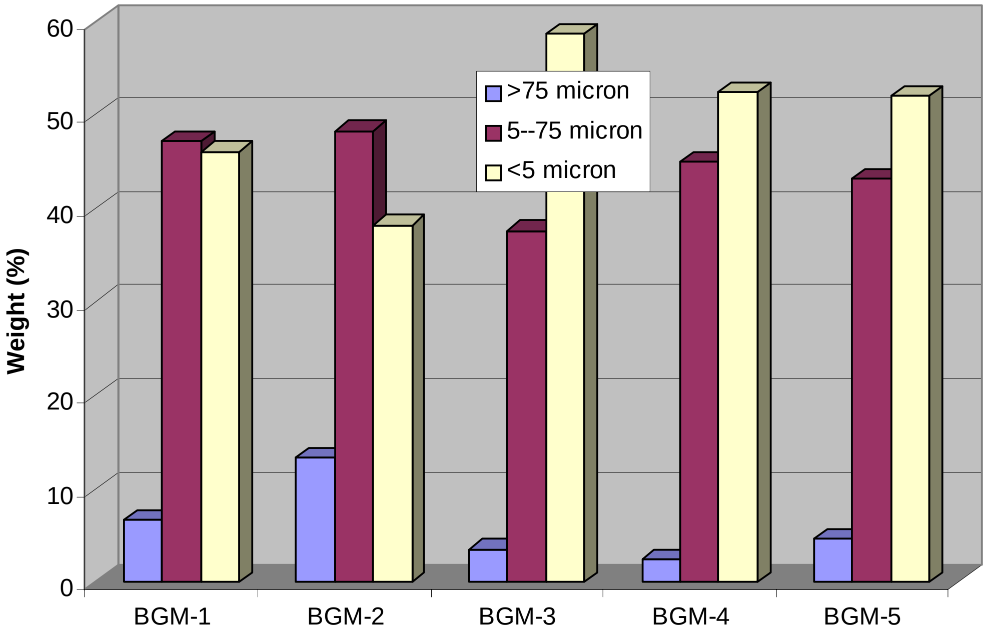

Figure 1. Weight percentages of the various size fractions in the bulk material.

3.2 Chemical composition

The chemical compositions of the coarse and fine fractions are given in Table 2. Silica and Al_2O_3 dominate composition of the coarse fraction. With some exceptions, all other elements are well below 1% in all samples. The exceptions are 2.4% Fe_2O_3 in BGM-2 and >1% K_2O in BGM-3 and BGM-4. The SiO_2/Al_2O_3 ratios are greater than that of pure kaolinite, confirming that significant quartz is present in the coarse fractions.

The fine fraction of all samples contains significantly less silica compared to the coarse fraction, and their SiO_2/Al_2O_3 ratio is close to that of pure kaolinite (1.18), confirming that the fine fractions predominantly consist of kaolinite. There are, however, some minor impurities, mainly 1-2% Fe and Ti oxides in BGM-2 and BGM-4.

The K_2O content of the fine fraction of BGM-3 and BGM-4 is 0.6 and 0.1% respectively, suggesting the K-bearing phase (probably mica), present in the coarse fraction, has mostly been removed.

Table 2. Chemical compositions of coarse and fine fractions expressed as %.

	BGM-1		BGM-2		BGM-3		BGM-4		BGM-5	
	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
SiO_2	66.5	44.9	64.2	44.7	65.0	45.9	67.5	44.5	59.5	45.0
Al_2O_3	23.5	38.5	24.1	37.1	23.7	38.8	21.8	37.5	28.3	38.7
Fe_2O_3	0.18	0.22	2.43	2.56	0.46	0.33	0.69	1.04	0.15	0.17
MnO	0.003	0.001	0.003	0.003	0.004	0.002	0.005	0.002	0.003	0.002
MgO	0.15	0.04	0.07	0.03	0.37	0.11	0.23	0.04	0.06	0.03
CaO	0.02	0.22	0.02	0.26	0.02	0.13	0.02	0.21	0.02	0.24
Na_2O	0.03	0.01	0.07	0.02	0.05	0.03	0.06	0.01	0.02	0.02
K_2O	0.59	0.08	0.17	0.07	1.97	0.59	1.16	0.12	0.13	0.08
TiO_2	0.62	0.77	0.39	0.13	0.82	0.52	0.76	1.48	0.99	0.90
P_2O_5	0.033	0.301	0.007	0.185	0.011	0.105	0.021	0.175	0.007	0.225
Total*	91.6	85.1	91.4	85.2	92.4	86.5	92.3	85.2	89.2	85.4
SiO_2/Al_2O_3	2.83	1.17	2.66	1.20	2.74	1.18	3.09	1.19	2.10	1.16

* The totals are less than 100 % due to loss of structural water on ignition.

3.3 Mineralogy

3.3.1 X-ray diffraction

Semi-quantitative mineralogy of the coarse and fine fractions is given in Table 3. Kaolin and quartz are the dominant minerals in the coarse fraction of all samples, which is consistent with their chemical composition. Traces of mica are also present in the coarse fraction of all samples except BGM-2.

The fine fraction consists predominantly of kaolin. Quartz, present in the coarse fractions, has been completely removed during separation of the fine fraction. Traces of Fe oxides are present in BGM-2 and BGM-4, and anatase in BGM-4.

Table 3. Mineralogy of the coarse and fine fraction of BGM kaolins.

Sample No.	Coarse fraction		Fine fraction	
	Major	Minor/traces	Major	Traces
BGM-1	kaolin, quartz	mica	kaolin	
BGM-2	kaolin, quartz		kaolin	Fe oxides*
BGM-3	kaolin, quartz	mica	kaolin	mica
BGM-4	kaolin, quartz	mica	kaolin	Fe-oxides*, anatase*
BGM-5	kaolin, quartz	mica	kaolin	

*Presence inferred from the chemical composition.

Kaolin is the only major Al-bearing material in both coarse and fine fractions. Therefore, the kaolin content in each fraction can be calculated from the Al_2O_3 content. Some samples contain mica, but the amount is so small that it will only result in a <1% error. Kaolin contents calculated by this procedure, and expressed as a percentage of the bulk material rather than each fraction, are shown in Figure 2.

The kaolin content of the <5μm fraction ranges from 38 to 58%. The sample BGM-2 has the minimum kaolin in the fine fraction, whereas BGM-3 has the maximum. The kaolin content of the 5-75μm fraction ranges from 2 to 19 % of the bulk materials. BGM-2 and BGM-5 have more in this fraction due to poor dispersion of clay.

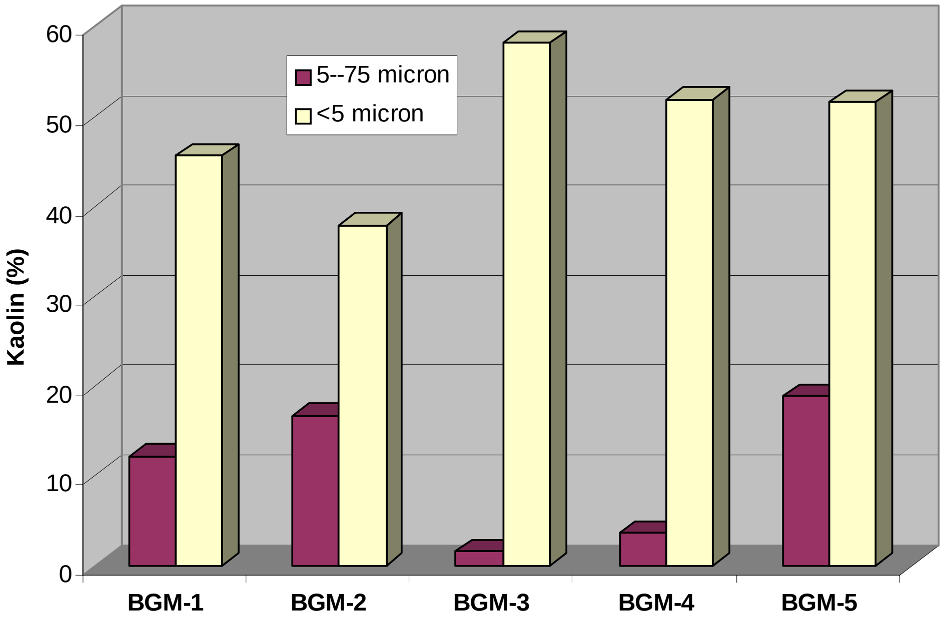

Figure 2. The kaolin content of the 5-75 and <5μm fractions, expressed as percentage of the bulk material.

3.3.2 Scanning electron microscopy

Undisturbed samples and clay concentrates were investigated under the SEM to determine the morphology of kaolin aggregates in the ore and the detailed characteristics of kaolin crystals. In particular, SEM analysis will distinguish kaolinite from halloysite on the basis of crystal morphology. The two kaolin polymorphs have almost identical chemical composition and crystal structure so that X-ray diffraction and chemical composition are unable to differentiate them.

SEM micrographs for the undisturbed samples and clay concentrates are shown in Figures 3-11. Undisturbed specimens show a very open fabric, with abundant voids between kaolin aggregates and quartz grains. An open fabric allows ready dispersion of ore in a wet or dry process. Kaolin aggregates are also very porous, which is a desirable characteristic for delamination of the aggregates into individual crystals.

Table 4. Relative contents of kaolinite and halloysite in the fine fraction.

Sample	Kaolinite	Halloysite
BGM-1	major	traces
BGM-2	minor	major
BGM-3	major	minor
BGM-4	major	traces
BGM-5	minor	major

High resolution SEM of kaolin concentrates showed that both kaolinite and halloysite occur in BGM kaolins. The samples BGM-1, BGM-3, and BGM-4 consist predominantly of kaolinite, whereas BGM-2 and BGM-5 consist of halloysite.

Both kaolinite and halloysite have extensive commercial applications. It is advantageous that both kaolin types occur in the BGM deposit, so that a range of products can be produced. Relative abundances of kaolinite and halloysite in the fine fraction are given in Table 4.

3.3.3 Brightness

Brightness of unfired and fired kaolins is given in Table 5. Brightness of unfired samples ranges from 67 to 73%. The variation in unfired brightness cannot be related to differences in mineralogy or chemical composition determined by XRF. It may be due to subtle differences in the type and content of organic matter, type of Fe oxide phases, particle size of impurities etc.

Table 5. ISO brightness (%) of fired and unfired BGM kaolins.

Sample No.	Unfired brightness	Fired brightness
BGM-1	67	89
BGM-3	73	89
BGM-4	68	76
BGM-5	72	89

BGM-2 has a reddish brown colour. Not analysed for brightness.

Brightness of fired kaolins ranges from 76 to 89%. Except BGM-4, all samples show significant increase in brightness upon calcination. The relatively poor fired brightness of BGM-4 (76%) appears to be due to >1% Fe_2O_3 and TiO_2 contents of this sample. Calcination generally enhances brightness of unfired kaolin. However, improvement achieved for BGM kaolins, from as low as 67% to 89%, is exceptional. BGM kaolins may contain some colloidal organic matter, destruction of which upon calcination results in an exceptionally bright product.

4.0 DISCUSSION

BGM samples contain up to 55-70% kaolin in their bulk material, which compares quite favourably with kaolin contents of many commercially viable deposits (Table 6).

BGM kaolins are very soft and friable, and retain the fabric of the parent rock. They disperse in water readily, and aggregates and books of kaolin separate into individual kaolin particles with minimal energy. The friable nature of these kaolins makes them suitable for both wet and dry processing methods.

Table 6. Clay content of some commercial kaolin deposits (Pickering and Murray, 1994).

Deposit	Clay content
Bavaria, Germany	12%
Cornwall, England	10-40%
Weipa, Australia	40-70%
Prosyanovski, Ukraine	30-50%
Florida, USA	15%
California, USA	20-25%
New Zealand	50%

The kaolin content of the fine fraction ranges from 38 to 58% of the bulk ore (Figure 2), which represents 70-97% of the total kaolin present in the ore. Although the current yield is quite high, it can be further increased by delamination, a standard component of modern wet processing methods.

The fine kaolin fraction appears to be free of quartz, which is an encouraging characteristic in view of the fine-grained nature of the bedrock. Impurities of mica, Ti and Fe oxides are also minimal in most samples, although the samples were taken at random.

BGM kaolins consist of both relatively pure kaolinite and halloysite. Most kaolin deposits contain some halloysite as a minor component without compromising critical properties. Halloysite dominated kaolins are valued for unique properties provided by its tubular crystals. The Maungaparerua deposit in New Zealand is well known for its halloysite that is used for whiteware and dinnerware manufacture because of its high fired whiteness and translucency (Murray, 1977, Pickering and Murray, 1994). It is also used in the paper, paint, plastic, and rubber industries.

Table 7. Typical brightness levels required for various kaolin applications (Pickering and Murray, 1994).

Application	Brightness GE	Price per short ton
Paper industry		
Filler	75-79	$52-64**
Coating grade	85-90%	$85-110
Calcined kaolin	89-94	$323-470
Ceramic applications		
Sanitaryware	75-80	NA
High strength	79-83	NA
Paints/plastics	75-80	NA
BGM kaolin		
Uncalcined	72-73 (+2)*	
Calcined	89 (+2)	

*ISO brightness is 1-2 unit lower than GE brightness.
** 1994 price in US dollars. NA: not available.

4.1 Processing methods and brightness

There are two basic methods of processing kaolin: a dry process and a wet process, shown schematically in Figures 12 and 13, respectively. The dry process is relatively simple, in which crude clay is crushed, dried, and pulverized in a roller mill. Relatively pure kaolin is then separated from quartz and other coarse grained impurities by air floatation. The dry process has lower cost, lower yields and lower brightness. Its products are mainly used as fillers in the paper industry.

The wet process is more complex. Crude clay is made into a slurry, dispersed and fractionated to remove coarse and soluble impurities. Large kaolin aggregates are delaminated to increase the fine fraction yield. The kaolin concentrate is given various beneficiation treatments, depending on the type of impurities present, to improve brightness. Desired size fractions are separated using continuous centrifuges to produce final products of the highest quality for the paper coating industry.

Laboratory processing of BGM kaolins in this study can best be compared with dry processing methods. The samples were dispersed in water, but no beneficiation treatment to improve brightness was given. Therefore, the brightness measurements can only be compared with that of dry processed kaolins or kaolins processed in a similar process.

BGM samples have an ISO brightness of up to 73%, which is comparable with unbeneficiated (dry grade) kaolins produced from well-known commercial deposits. It can be improved to greater than 86%, using appropriate brightness beneficiation treatments, to produce paper coating grade kaolins. An indication of this potential is provided by the Prosyanovski kaolin deposit in Ukraine, which is similar to BGM kaolins in many respects (Table 7).

Pickering and Murray (1994) report that "After transport to the processing area, crude clay from Prosyanovski is blunged at a ceramic plant in washing drums and degritted with sand rakes. No centrifuging or leaching is done at this plant, which produces a product of approximately 52% finer than 2 μm at 72-73% ISO brightness. The same slurry is also fed from the ceramic plant to the paper coating plant, where it is centrifuged to approximately 75% finer than 2μm and leached to an 84+ and 86+ ISO brightness product."

Murray, Table 7. Comparison of some properties of BGM deposit and Prosyanovski deposit (Pickering and 1994).

	Prosyanovski deposit	BGM deposit
Deposit type	residual	residual
Kaolin content	30-50%	55-70%
Unbeneficiated ISO brightness	72-73	73
Beneficiated ISO brightness	>86	?
Halloysite	present	present
Montmorrilonite impurity	up to 10%	nil

Clearly, the unbeneficiated brightness of BGM kaolins is comparable with those of commercially profitable kaolin deposits. Appropriate brightness beneficiation treatments are expected to yield high brightness paper coating grade kaolins from the BGM deposit.

4.2 Calcined kaolins

Calcination is a widely used process to produce high-grade products. In laboratory scale tests, it is used to test fired brightness for application of kaolin in the ceramic industry. On calcination, kaolin converts to a mixture of mullite, silica-alumina spinel, and cristobolite that is generally whiter, brighter and has better opacity than unfired kaolin. Subtle chemical impurities in the kaolin structure, discrete mineralogical impurities, particle size, and crystallinity determine the brigtness of fired kaolin.

The brightness of BGM kaolins, except BGM-4, increases markedly with calcination. Such a large increase could be due to destruction of colloidal organic matter, although it is not fully understood. The fired brightness of BGM kaolins nearly equals the specification for calcined kaolins produced by firing beneficiated kaolins. It is expected that calcination of BGM kaolins, after appropriate beneficiation treatments, would result in an exceptionally high fired brightness.

5.0 CONCLUSIONS

The following conclusions are drawn from this preliminary study.

- BGM kaolins contain 50-70% kaolin, most of which (70-90%) can be separated into a <5 μm fraction.
- There are minimal fine-grained impurities in the <5μm fraction of most samples.
- Brightness of BGM kaolin is comparable with that of unbeneficiated kaolin of commercially viable deposits, and is sufficient for application in ceramics and as filler in the paper, paint, and plastics industries.
- Paper coating grade kaolins may be produced from BGM kaolins using appropriate treatments to increase brightness. Response of BGM kaolins to common beneficiation treatments needs to be determined.
- The brightness of calcined, unbeneficiated BGM kaolin is remarkably high, and matches brightness of calcined versions of beneficiated kaolins of other deposits.
- Both halloysite and kaolinite type kaolins can be produced from the BGM deposit.

6.0 FUTHER WORK

Conclusions made in this study are based on only five samples that were collected randomly with respect to lithology and geomorphic setting. The samples were analysed only for selected major characteristics with out any beneficiation. Current results are very encouraging and, therefore, warrant following work to make a full assessment of the quality and quantity of the BGM kaolin.

- Systematic sample kaolin in a range of geological and geomorphological units.
- Analyse samples for particle size, brightness, chemical composition, and mineralogy.
- Determine the response of BGM kaolins to common brightness beneficiation methods.
- Relate mineralogy, brightness, and particle size to geological and geomorphological units to develop a predictive model.

ACKNOWLEDGEMENTS

David Burton is thanked for providing samples from the Boddington Gold Mine. Ian Robertson, Mel Lintern and Matthias Cornelius kindly reviewed the manuscript. Their comments are much appreciated. Mike Hart carried out the XRD and XRF analyses.

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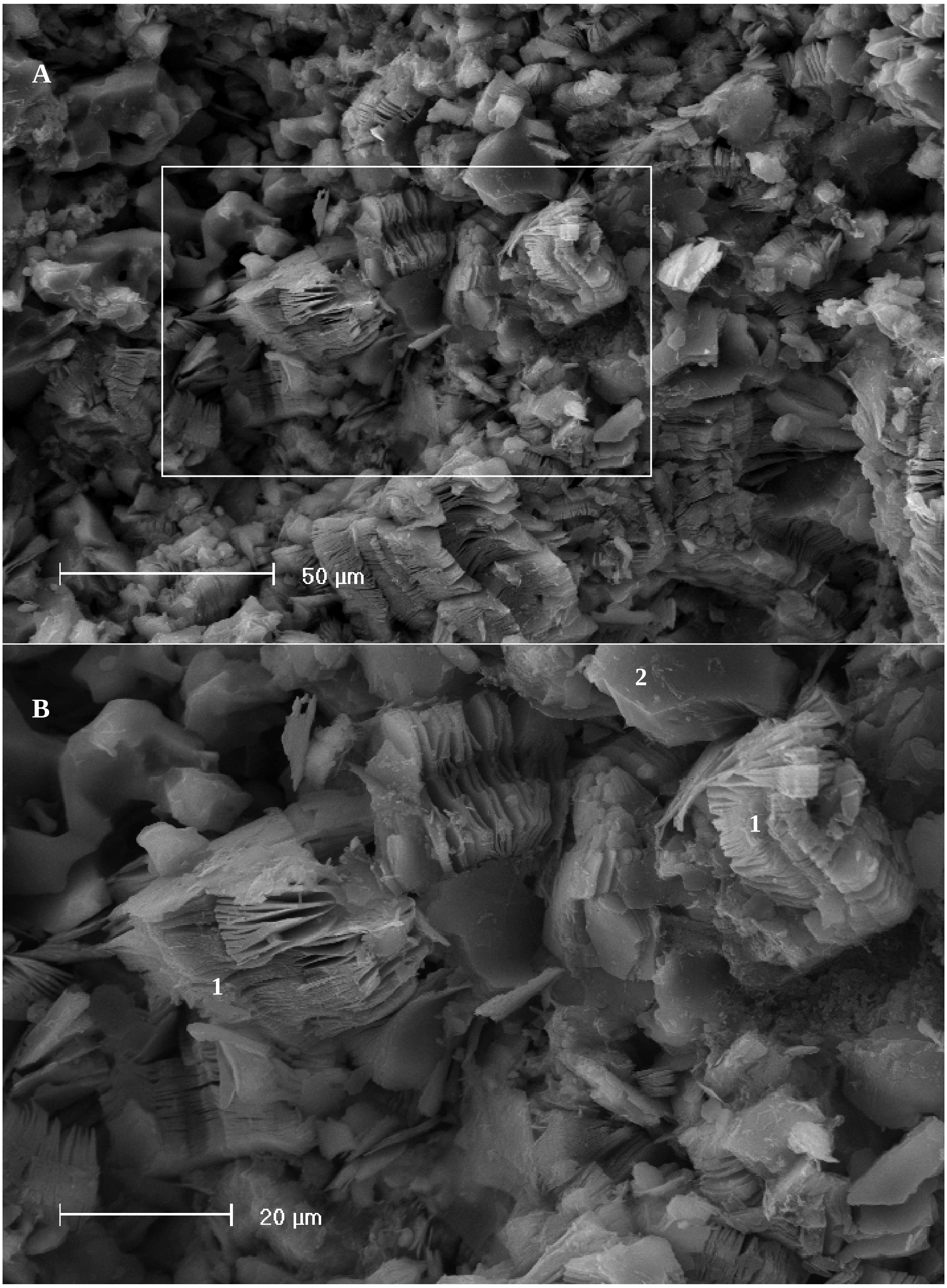

Figure 3. SEM micrographs of undisturbed surfaces of sample of BGM-1. Partly expanded books of kaolinite (1), slivers of quartz (2) and abundant voids are present.

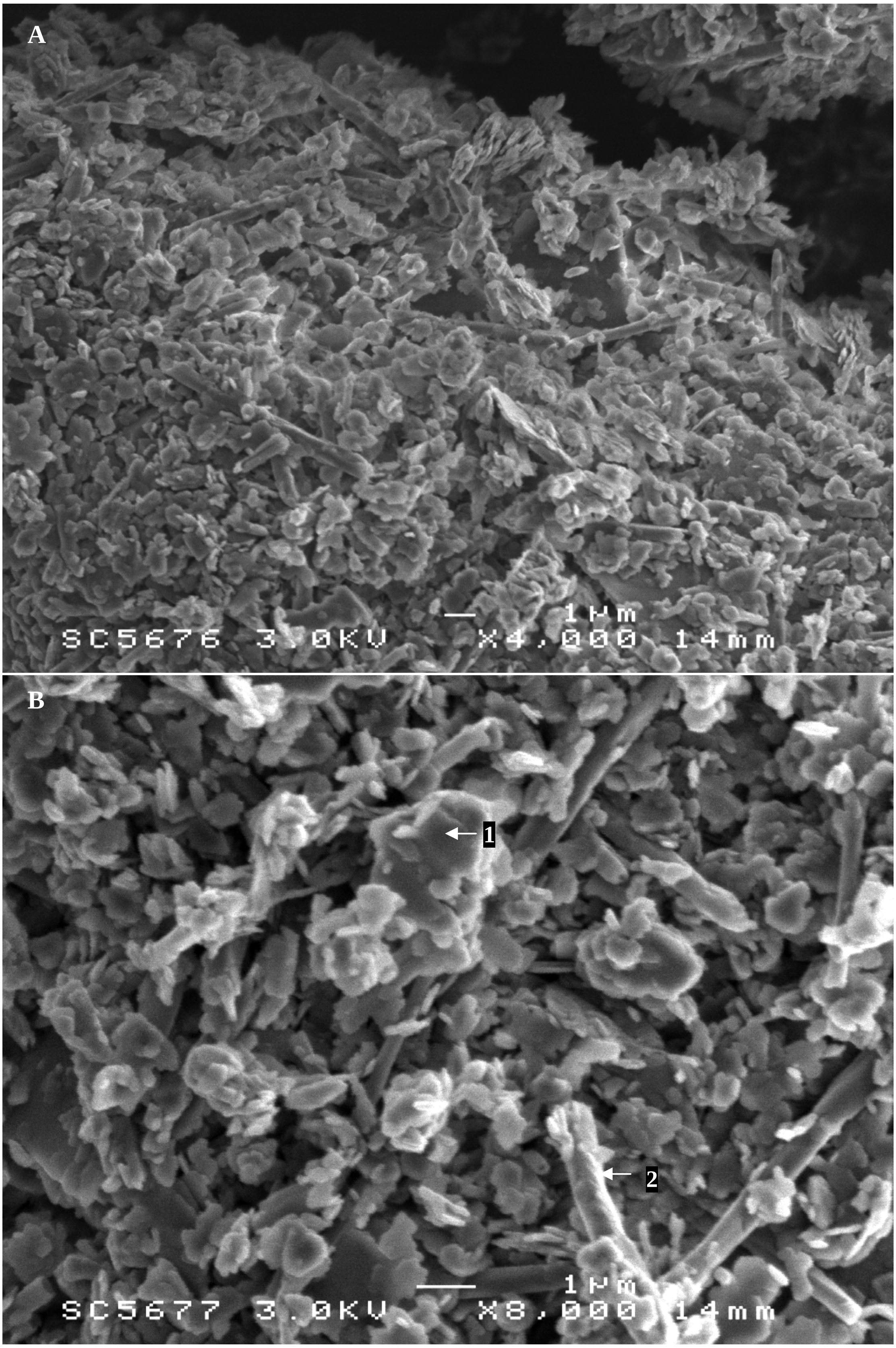

Figure 4. SEM micrographs of fine fraction of BGM-1, showing a mesh of tabular kaolinite crystals (1) and some long tubes of halloysite (2).

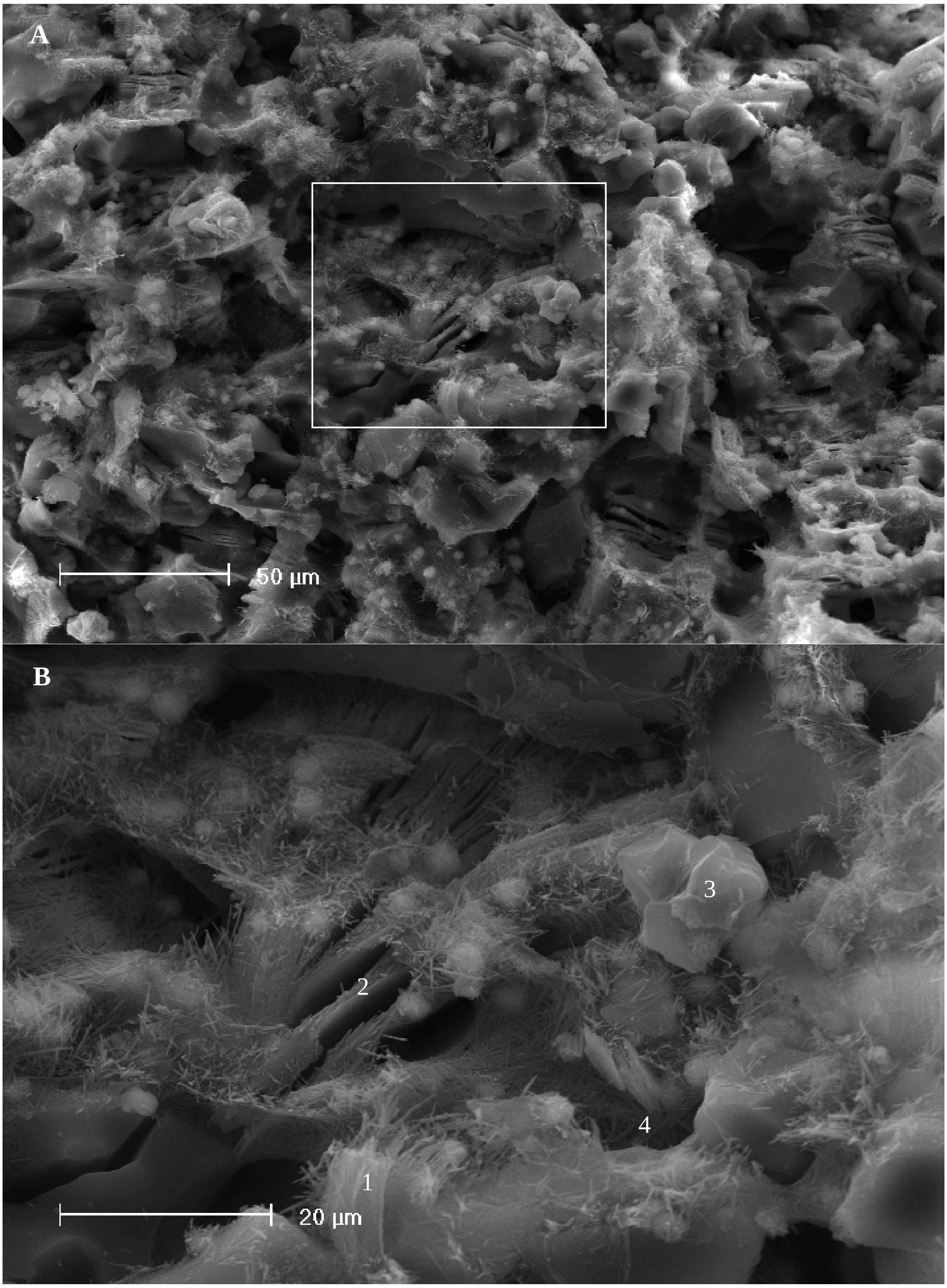

Figure 5. SEM micrographs of undisturbed surfaces of sample of BGM-2. Aggregates of very fine needles of halloysite (1) and some books of kaolinite (2), irregular grains of quartz (3) and abundant voids (4) are present. B is an enlargement of A.

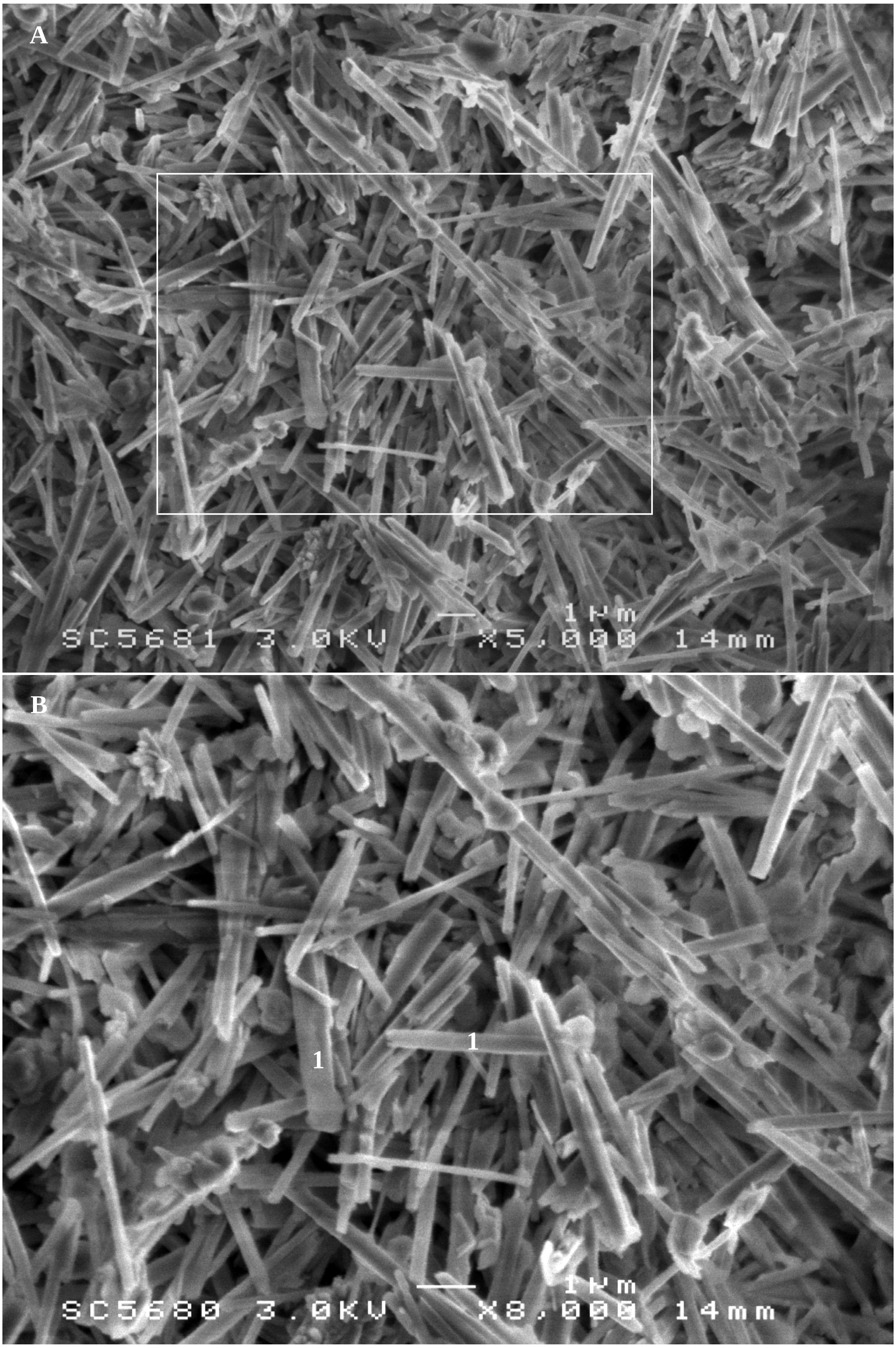

Figure 6. SEM micrographs of fine fraction of BGM-2, showing a mesh of mostly tubes and laths of halloysite (1). B is an enlargement of A.

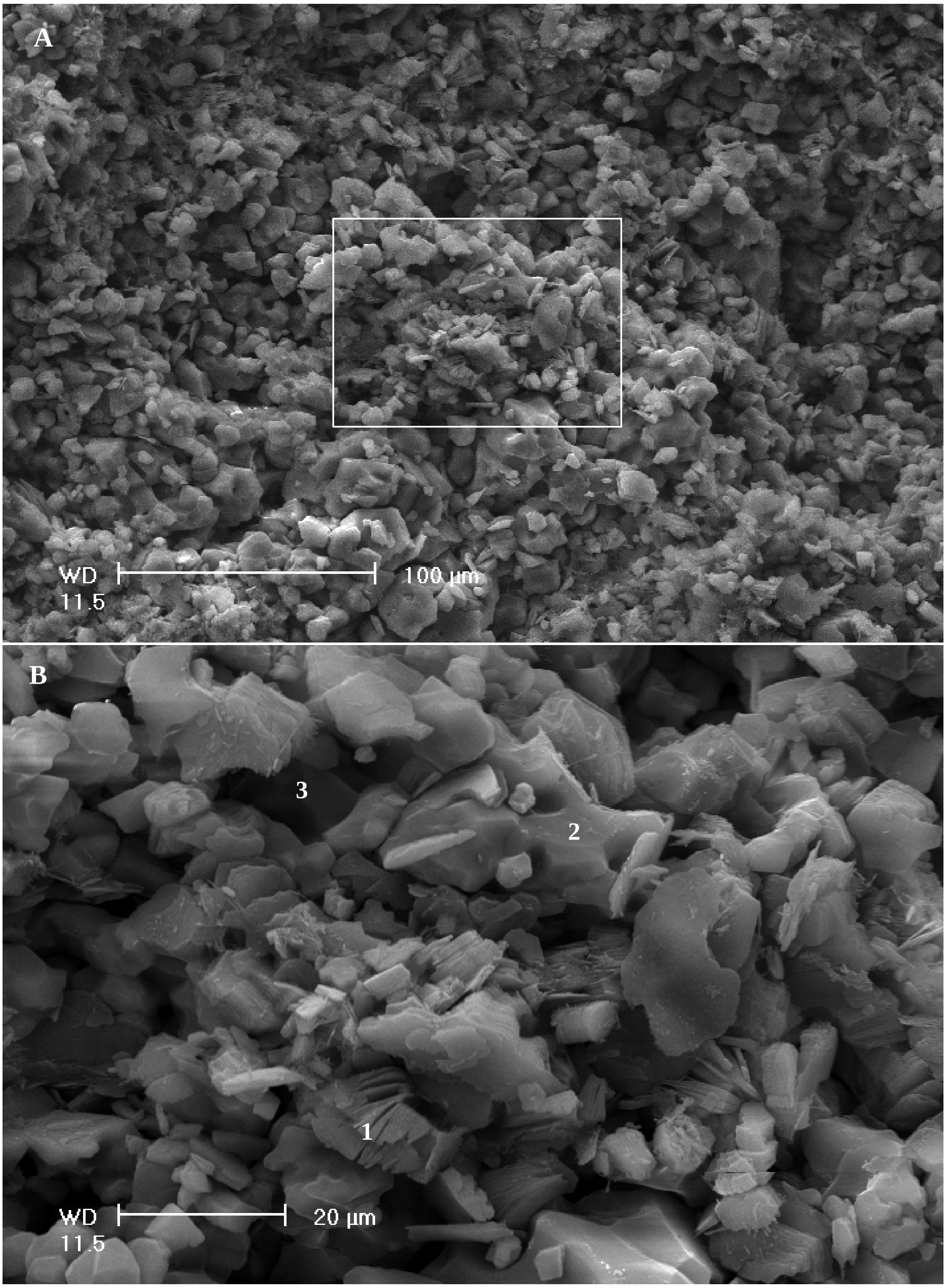

Figure 7. SEM micrographs of undisturbed surface of sample of BGM-3. Partly expanded books of kaolinite (1), irregular grains of quartz (2) and intercrystalline voids are present (3). B is an enlargement of A.

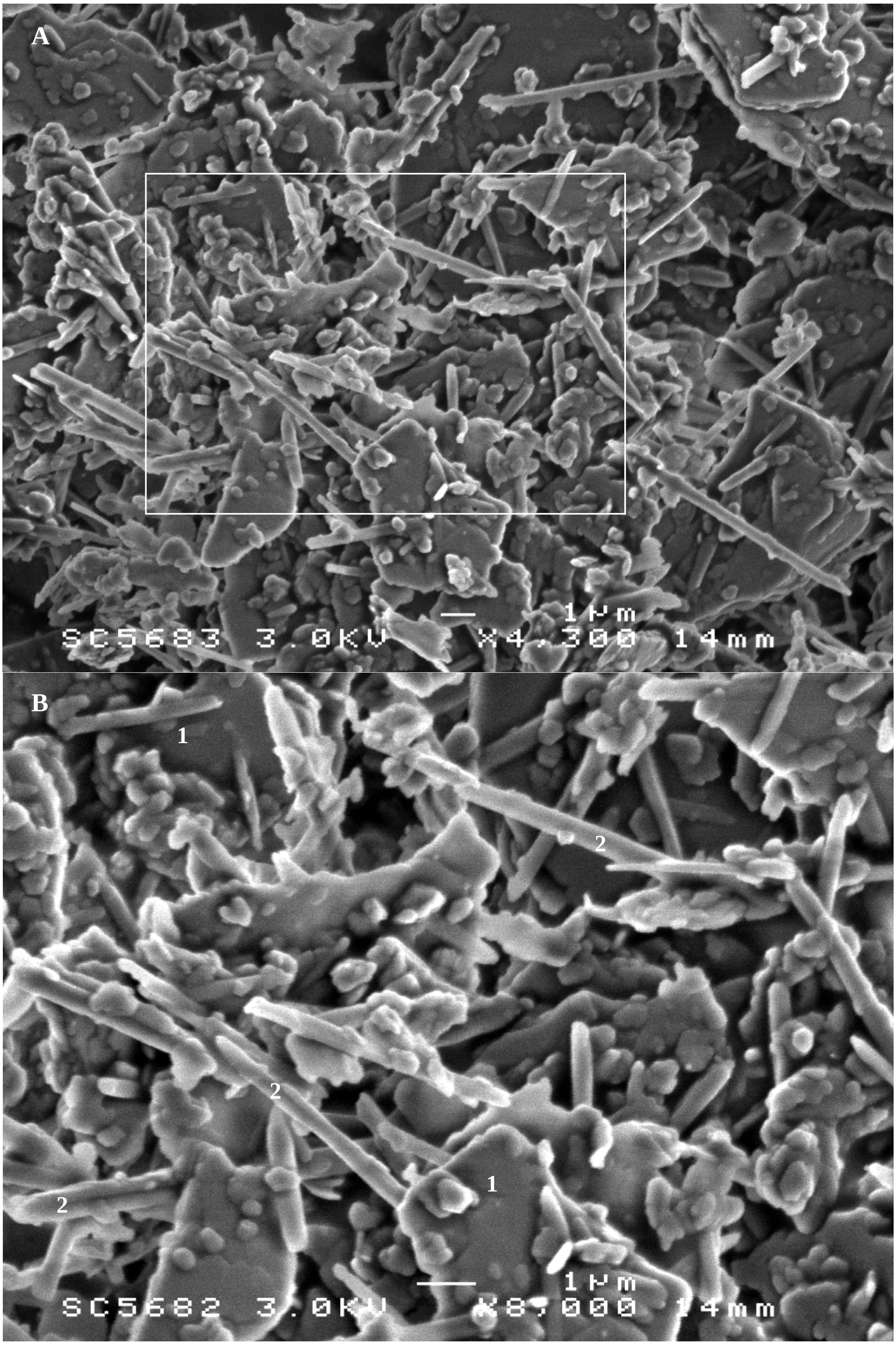

Figure 8. SEM micrographs of the fine fraction of BGM-3, showing a mesh of platy kaolinite (1) crystals and some tubes and laths (2) of halloysite.

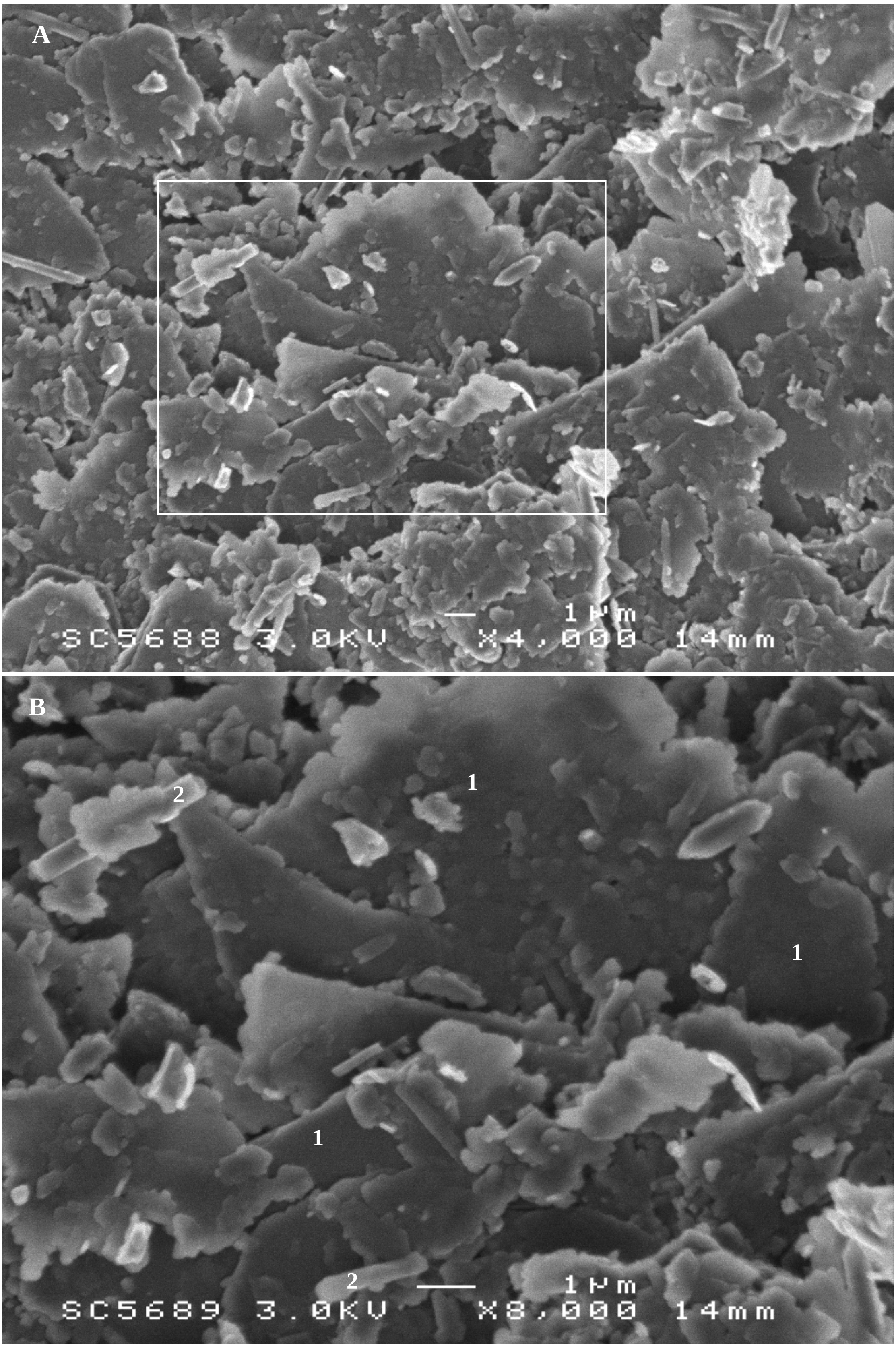

Figure 9. SEM micrographs of the fine fraction of BGM-4, showing mostly a mesh of platy kaolinite crystals (1) and very few short tubes of halloysite. B is an enlargement of A.

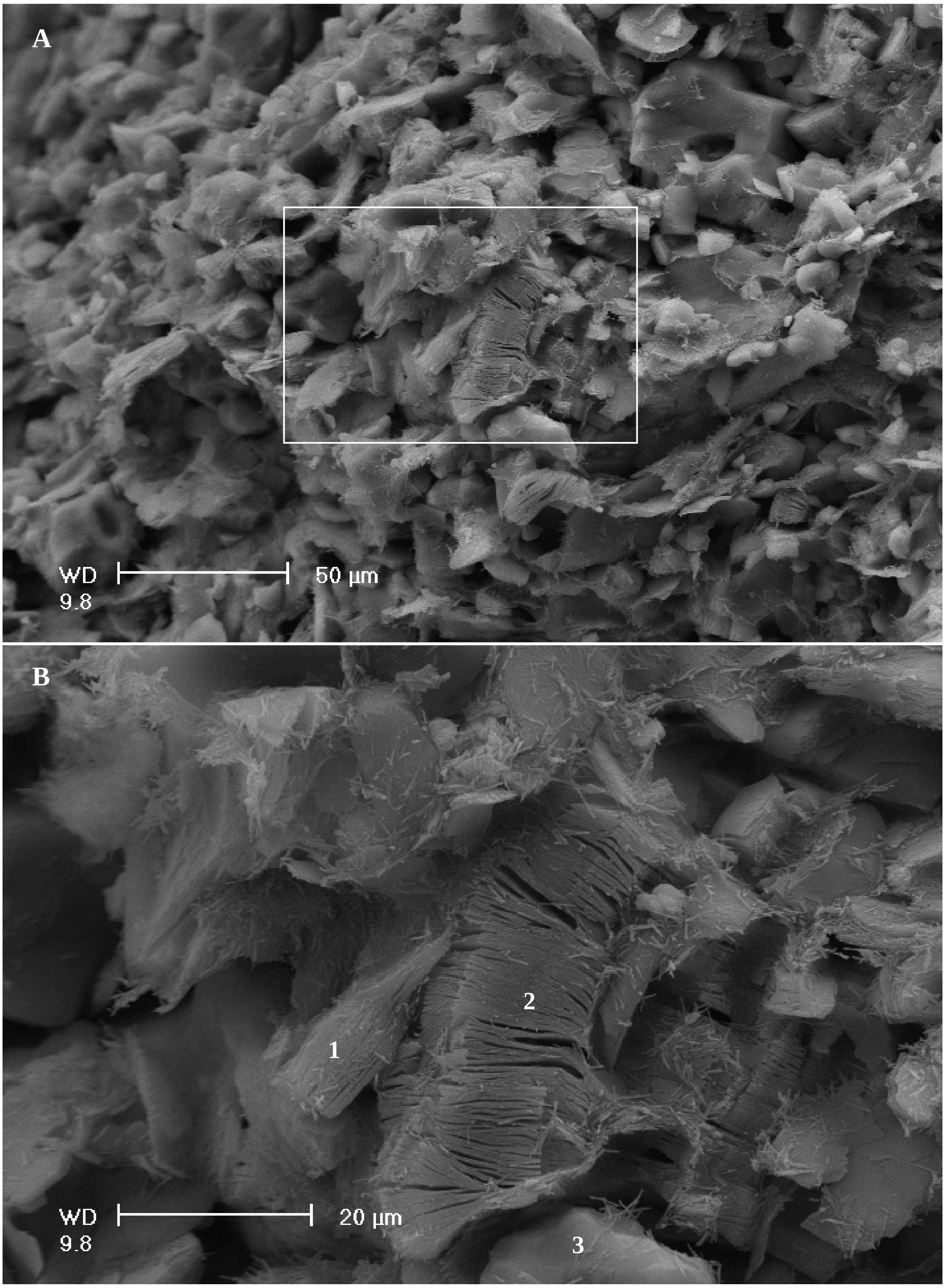

Figure 10. **SEM micrographs of undisturbed surfaces of sample of BGM-5. Aggregates of very fine needles of halloysite (1), partly expanded books of kaolinite (2), irregular grains of quartz (3) and intercrystalline voids are present. B is an enlargement of A.**

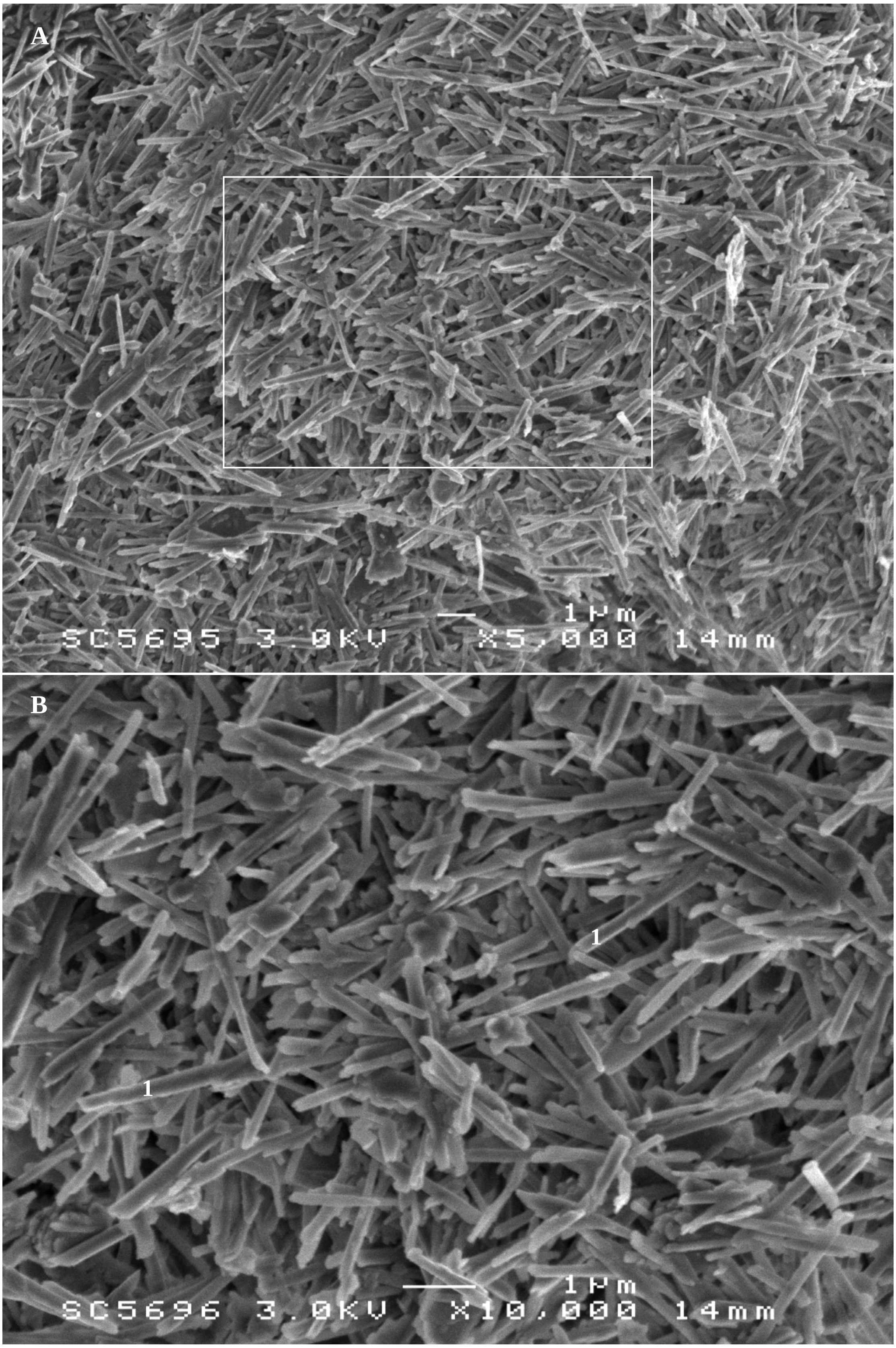

Figure 11. SEM micrographs of the fine fraction of BGM-5, showing mostly a mesh of halloysite tubes and laths. B is an enlargement of A.

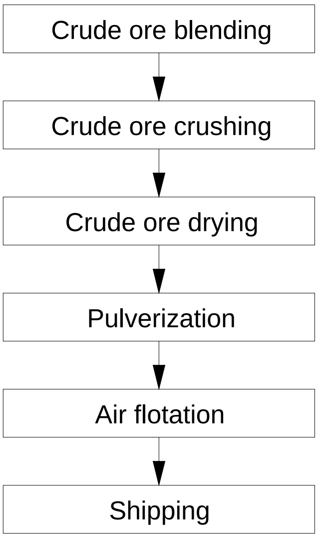

Figure 12. Flow chart showing a typical dry processing method (Prasad et al. 1991).

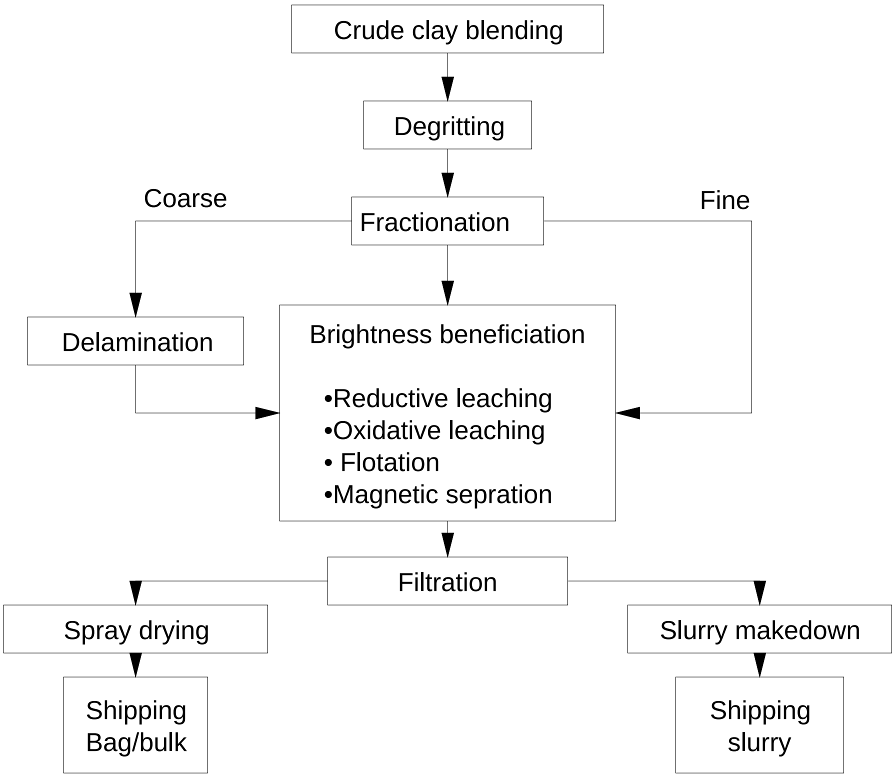

Figure 13. Flow chart showing a typical wet processing method (Prasad et al. 1991).