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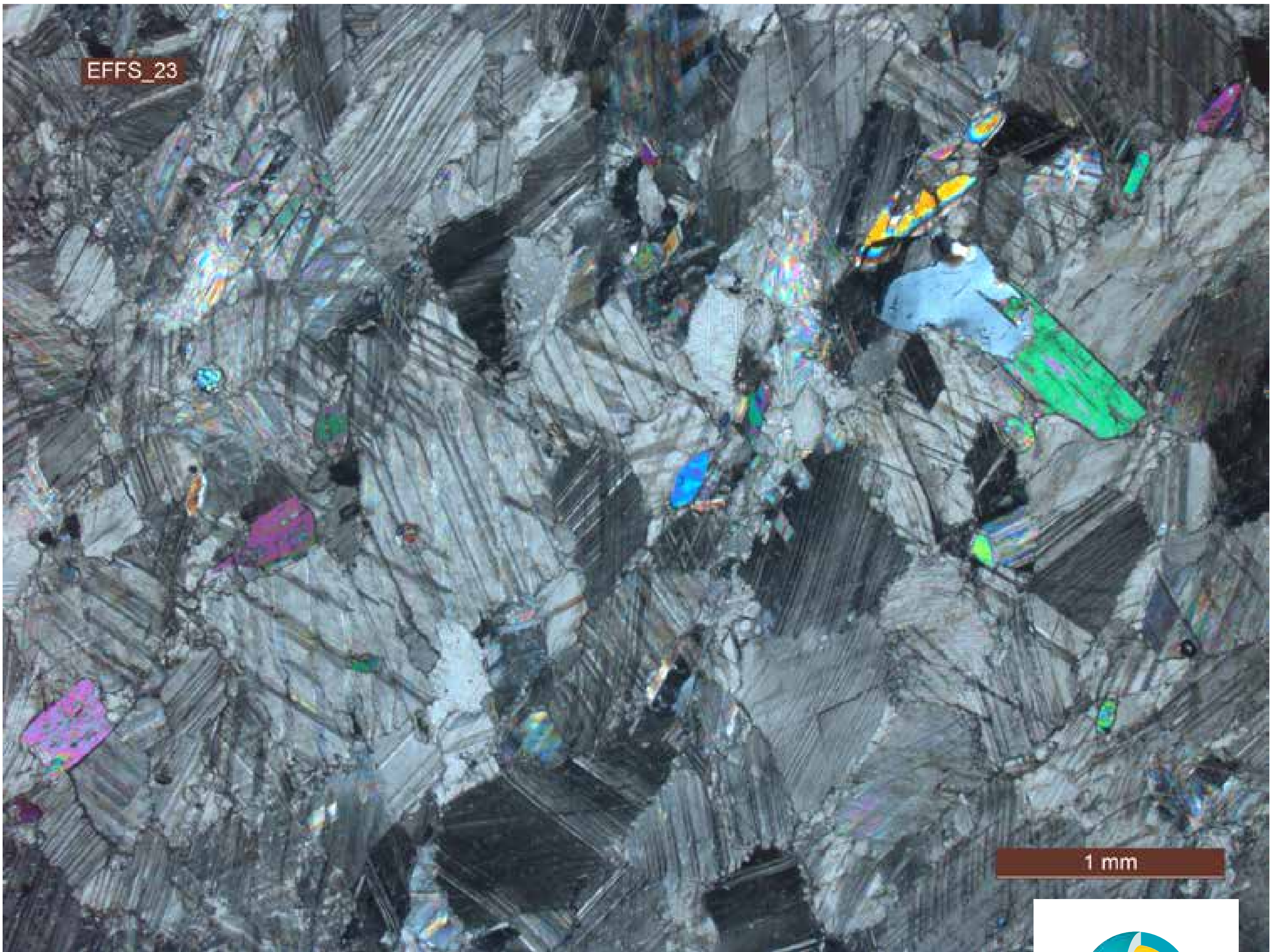
Emerging role of applied mineralogy in agricultural acid soil management: A case study on Minare and Moga carbonate rock resources in Ethiopia

Tegist Chernet, Tero Korhonen, Kristian Lindqvist and Mia Tiljander

GTK Open File Research Report 52/2019



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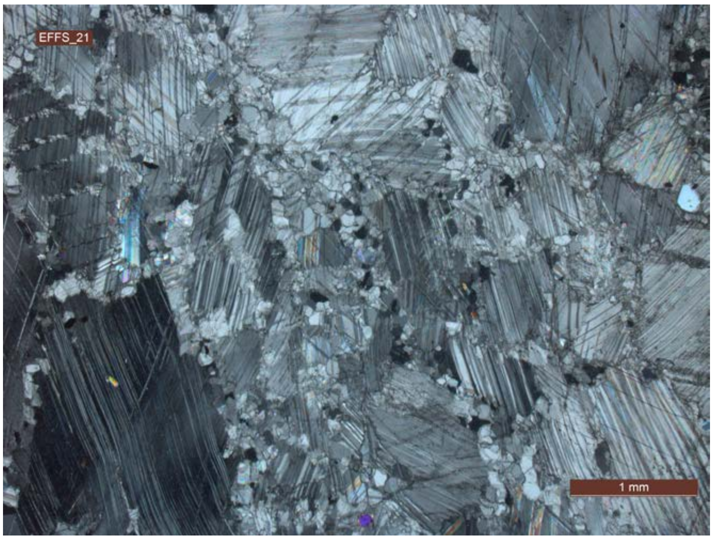

Unless otherwise indicated, the figures have been prepared by the authors of the report.

Front cover: Recrystallization at grain boundary, twinning structure and fracturing in the Minare marble, Oromia regional state, Ethiopia. Image: Tegist Chernet, GTK.

Layout: Elvi Turtiainen Oy

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Ethiopia is endowed with a variety of carbonate rock resources, which are essential in reclamation of acidic soils for improved grain production. Given increasing demand for agricultural lime and its bulky nature, it is important to ensure not only availability of the resource, but also its quality. Hence, two major carbonate deposits in Ethiopia, Minare in Oromia and Moga in Benishangul Gumuz, were characterized mineralogically and technically to determine their suitability as agricultural lime. The neutralization ability of lime depends mainly on its composition of carbonate resources ($CaCO_3$-equivalents), while its reactivity and agronomic effectiveness depend mainly on its fineness.

Minare limestone is dominated by calcite (up to 54 wt. % CaO), but poor in MgO. The Moga carbonate resource is a marble, which is both calcitic (up to 57 wt. % CaO) and dolomitic (up to 19 wt. % MgO). Compositionally, both resources can be utilized as agricultural lime for the vast acid-affected agricultural and pastoral lands nearby. The presence of minor amount of silicates, oxides, and sulfides produces no significant change in the quality of the lime.

Bond Rod Mill Work Index (BRMWI), expressed in kWh/t, was determined to characterize the grindability of the rocks in terms of ease of pulverization and energy consumption to produce the required degree of fineness. The tests revealed that the Moga marble, which is traditionally defined as hard rock, requires less energy (about 8.8 kWh/t) than the Minare limestone (about 15.3 kWh/t), indicating that grindability depends on the mineralogical characteristics of the rock. Hence, applied mineralogical studies and comminution tests are necessary before establishing lime production sites and installing crushing plants.

Keywords: applied mineralogy, acid soil, marble, limestone, grindability, lime, GTK Mintec, GTK research laboratories

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1 INTRODUCTION

1.1 Agriculture in Ethiopia

The Ethiopian economy is highly dependent on rain-fed agriculture, accounting for half of gross domestic product and 80% of total employment. However, Ethiopia's agricultural production suffers from soil degradation caused by overexploitation, overgrazing and erosion, deforestation, poor infrastructure, and periodic drought. Due to problems in agricultural production, as many as 5.6 million people were identified as requiring emergency food relief in 2017, at an estimated cost of 713 million USD (Joint Government and Humanitarian Partners' Document, Addis Ababa 2017). Prolonged and severe drought in 2016/2017, followed by heavy seasonal rainfall and flooding during 2018, has left an estimated 7.9 million people facing severe food insecurity (Food assistance fact sheet, USAID 2018). This is a significant increase on the 2.9 million people projected to require food assistance during 2015 (Joint Government and Humanitarian Partners' Document, Addis Ababa 2015). Yet, Ethiopia has potential for self-sufficiency in grain and for expanding its exports of livestock, grain, vegetables and fruits. One key factor in this potential is grain yield per unit area. Increasing yield involves several factors like irrigation and use of proper pesticides and seeds, but also good health and quality of the soil. So far, little has been done to balance and improve the soils of Ethiopia, which in many places are too acidic for efficient grain production and nutrition security.

1.2 Applied mineralogy

Carbonate rock, the main source of agricultural lime, is widely used as an amendment to neutralize acid soils. With increasing demand for agricultural lime to apply on vast areas of acid soils, however, significant attention should be given to lime quality. The chemical composition and physical properties of carbonate rocks vary widely even within the same deposit, so it is important to assess these parameters prior to use. Compositional variations, the presence and amount of accessory minerals, nutrients or other elements, grain size, porosity and hardness can affect the suitability of carbonate deposits as a source of agricultural lime. Neutralizing value (NV) and particle size are well-established conventional criteria for evaluating lime quality. Neutralizing value of the liming material is expressed as percentage of calcium oxide (CaO) equivalents, which in turn depends on the rock composition. Grain size and hardness of the minerals affect crushability. Furthermore, particle size of the crushed material influences the surface area, and hence the rate of dissolution. The rate of dissolution can also be affected by the mineral composition of a given carbonate rock. At equal surface area and purity, the rate of dissolution decreases from calcite to dolomite to magnesite (Chou et al. 1989, Mackenzie & Lerman (ed.) 2006). All of these minerals have been identified in different agricultural limes.

Even the purest carbonate rocks (e.g., limestone, dolomitic limestone, dolomite, and their metamorphic equivalents) contain some accessory minerals, which in many cases form a considerable proportion of the mass. The commonest are quartz, mica, graphite, iron (Fe) oxides, and pyrite. Carbonate rocks also contain silicates, e.g., diopside, tremolite/actinolite, feldspar/plagioclase. Various kinds of garnet, spinel, forsterite, talc, zoisite, wollastonite, chlorite, tourmaline, epidote, chondrodite, biotite, titanite, and apatite may also occur, as well as small amount of pyrite, pyrrhotite, sphalerite, and chalcopyrite. These minerals are impurities in carbonate rocks and, when present in greater proportions, could affect the NV of agricultural lime produced from these rocks.

The concentrations of metals in agricultural lime are commonly low, according to McBride and Spiers

(2001). However, possible accumulation of trace elements to toxic levels in soils and the potential harm to the environment must be considered. For example, given the known affinity of Fe and manganese (Mn) oxides to scavenge toxic trace metals and metalloids, it is worth checking for high oxide contents, to assess the potential risk of soil and groundwater contamination from often voluminous lime application.

Hence, the two Ethiopian carbonate resources (at Minare, Oromia, and at Moga, Benishangul Gumuz) tested in this study were characterized mineralogically and technically, to determine their suitability as agricultural lime.

1.3 Minare and Moga carbonate rocks

Carbonate rock resources were identified within three major geological units in various regions of Ethiopia: in Proterozoic rocks (marble, limestone), in Mesozoic sedimentary sequences (limestone, dolomite, marl), and in Cenozoic sediments (limestone, dolomite, marl) (Kazmin 1972, Schlede 1989, Tefera et al. 1996). Extensive deposits of marble are also present in the Precambrian metamorphic terrains of northern and western Ethiopia (Heldal & Walle 2002, Walle et al. 2000). Among the known resources, Proterozoic limestone/dolomite deposits in western and central Ethiopia have considerable potential, as they are located close to the main areas of acid soils. Dolomitic limestone and marble deposits suitable for the production of agricultural lime and in close proximity to areas with strongly to moderately acid soils (pH <5.5) have been reported in western (Gojam, Wollega, Illubabur, Kaffa) and southern (Omo, Sidamo) Ethiopia (Abera 1994).

Based on existing information, Minare limestone and Moga marble were identified for both geological surveys and mineralogical studies (Fig. 1). The resources were targeted according to their different character, in order to study their suitability for liming purposes. Minare limestone is a thick sequence of mainly carbonate rocks of Mesozoic age found on a hilly basalt plateau near Minare village, some 65 km NNW of Holeta, Oromia region, at about

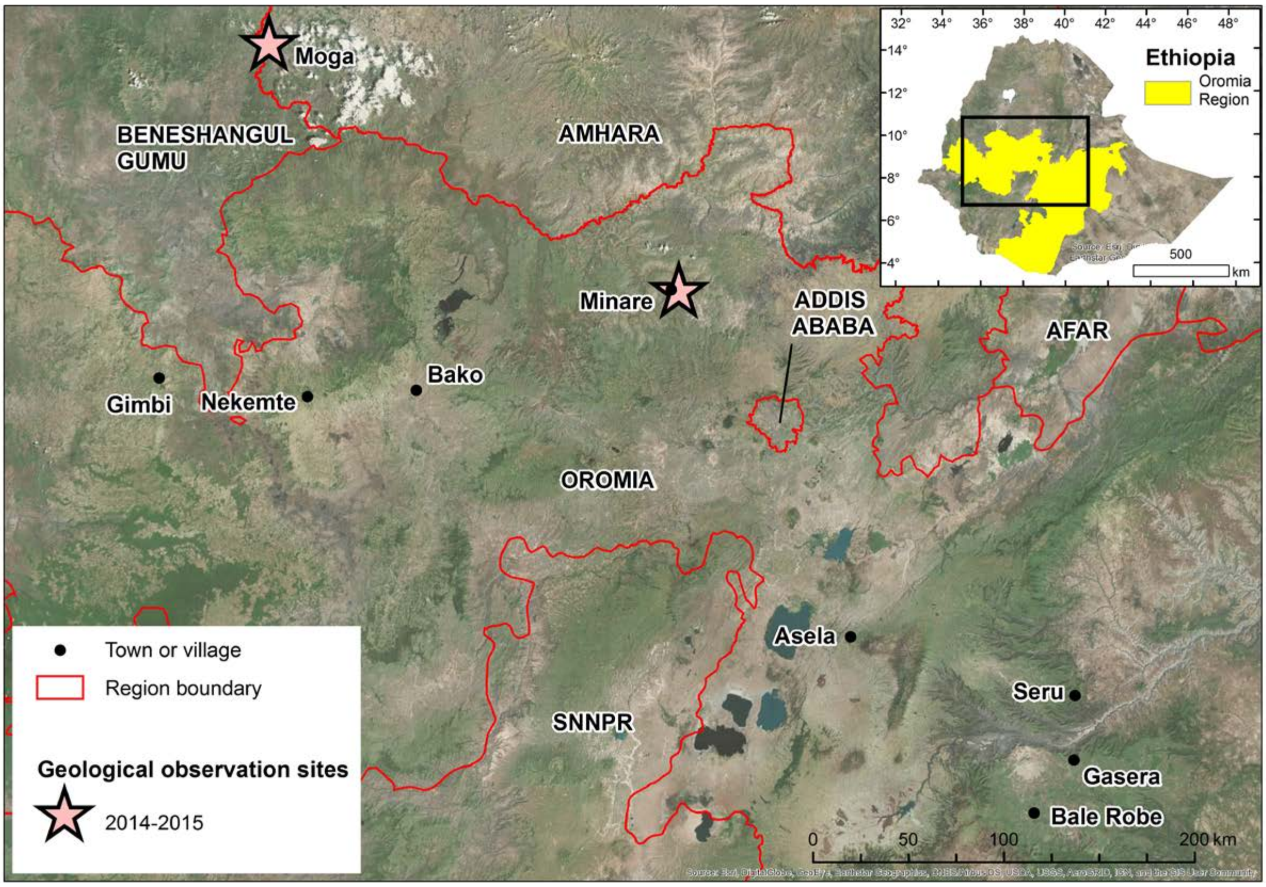

Fig. 1. Map showing the location of the study areas (Minare in Oromia region and Moga in Benishangul Gumuz region) in Ethiopia. (Map by Jussi Pokki, GTK)

2300 m a.s.l. The topography of the area consists of plains, hills, and valleys. The limestone is overlain by Paleogene volcanic rocks and underlain by interbeds of travertine, marl, and soft mudstone. Moga marble is found in Benishangul Gumuz and partly in Amhara Regional State, some 330 km NW of Addis Ababa and 27 km SW of Chagni town. Moga marble occurs in a Precambrian terrain which is outcropped as a window in Cenozoic Paleogene basalts. The marble is either rich in calcium carbonate, i.e. calcitic marble, or rich in magnesium carbonate, i.e. dolomitic marble.

2 SAMPLES AND ANALYTICAL METHODS

Representative rock samples taken from outcrops of Minare limestone and Moga marble were subjected to mineralogical studies, chemical analyses, and grindability tests (Table 1). A number of polished thin sections were prepared and examined for carbonate and other minerals, including their texture, under Leica reflection and transmission light microscope (LM). Microphotographs of major minerals were taken to illustrate observations on mineral content, grain size, and texture. A Joel scanning electron microscope (SEM) attached to an energy dispersive X-ray spectroscopy (EDS) (JEOL JSM 5900 LV) was employed to further identify and semi-quantitatively define calcite, dolomite, and other rarely occurring minerals. The SEM produces high-resolution back-scattered electron (BSE) images of the sample scanned with a focused beam of electrodes. Hence, very fine-grained minerals and features are easily observed and analyzed semi-quantitatively.

X-ray diffraction (XRD) analyses were also conducted at GTK Research Laboratories, to semi-quantitatively determine the mineral content of the rock samples. It was assumed that the sample crushing procedure homogenized the rock and that it was therefore sufficient to analyze one sub-sample of powder from each sample. Mineral phases were identified using Bruker's EVA-program with the ICDD (International Centre for Diffraction Data) mineral database PDF-Minerals 2013.

As the neutralizing ability of carbonate rocks largely depends on their CaO and magnesium oxide (MgO) content, selected samples were also analyzed for major oxides, plant nutrients, and minor base metals at the Geological Survey of Ethiopia (GSE), using atomic absorption spectroscopy (AAS).

Table 1. Samples of Minare limestone and Moga marble submitted for mineralogical studies and crushing tests at the Geological Survey of Finland (GTK) and Geological Survey of Ethiopia (GSE). LM = light microscopy, SEM = scanning electron microscopy, XRD = X-ray diffraction analysis.

LM and SEM	**XRD analyses**	**Crushing test**		**Chemical analyses**
GTK	GTK	GTK		GSE
Minare, Muger				
EFFS-2	EFFS-2	EFFS-2	2.8kg	
EFFS-52	EFFS-52	EFFS-52	2.4kg	EFFS-52
EFFS-3	EFFS-3			EFFS-3
EFFS-14	EFFS-14			EFFS-14
	EFFS-14 (powder)			
EFFS-7	EFFS-7		7.7kg	EFFS-7
Moga, BG				
EFFS-21	EFFS -21	EFFS-21	5.7kg	EFFS-21
EFFS-23	EFFS -23	EFFS-23	3kg	EFFS-23
EFFS-47	EFFS-47			EFFS-47
EFFS-39	EFFS-39			EFFS-38
EFFS-32				EFFS-36
EFFS-2 (dark)				
EFFS-2 (light)				
EFFS-3			8.7kg	

Grindability index tests were performed on samples of Minare limestone and Moga marble at GTK's Mintec Outokumpu pilot plant and bench-scale mineral processing laboratory, to determine ease of pulverization and the amount of energy required to produce standard agricultural lime.

3 MINERALOGICAL OBSERVATIONS AND ANALYTICAL RESULTS

3.1 Minare limestone, Oromia

Minare carbonate rock resource is dominated by limestone. In hand specimens, it is typically fine-grained and light grey, yellowish, or pure white in color. Based on microscope observations, the rock is composed primarily of anhedral (not well-developed crystal phases) calcite (65–95%) (Fig. 2), with very fine-grained crystalline calcite developed along fractures and pores. The largest calcite grains are about 300 µm in diameter, while those forming the matrix are only a few microns. Minor amounts of other minerals present include quartz, mica, zircon, apatite, Fe-oxide, Fe-titanium (Ti) oxides, copper-zinc (Cu-Zn) sulfides, titanite, garnet, epidote, feldspar, clay minerals, monazite, and xenotime (Fig. 2). Grain size varies from about 200 microns down to a few microns, but is on average 20 to 50 microns. However, the amount of quartz and other minor minerals varies within the same deposit. Silicates frequently fill cracks and any form of cavity.

The rock resembles an organic sedimentary rock, as the matrix is made up chiefly of ground shells and skeleton debris accumulated as sediment, which have been lithified into limestone. The

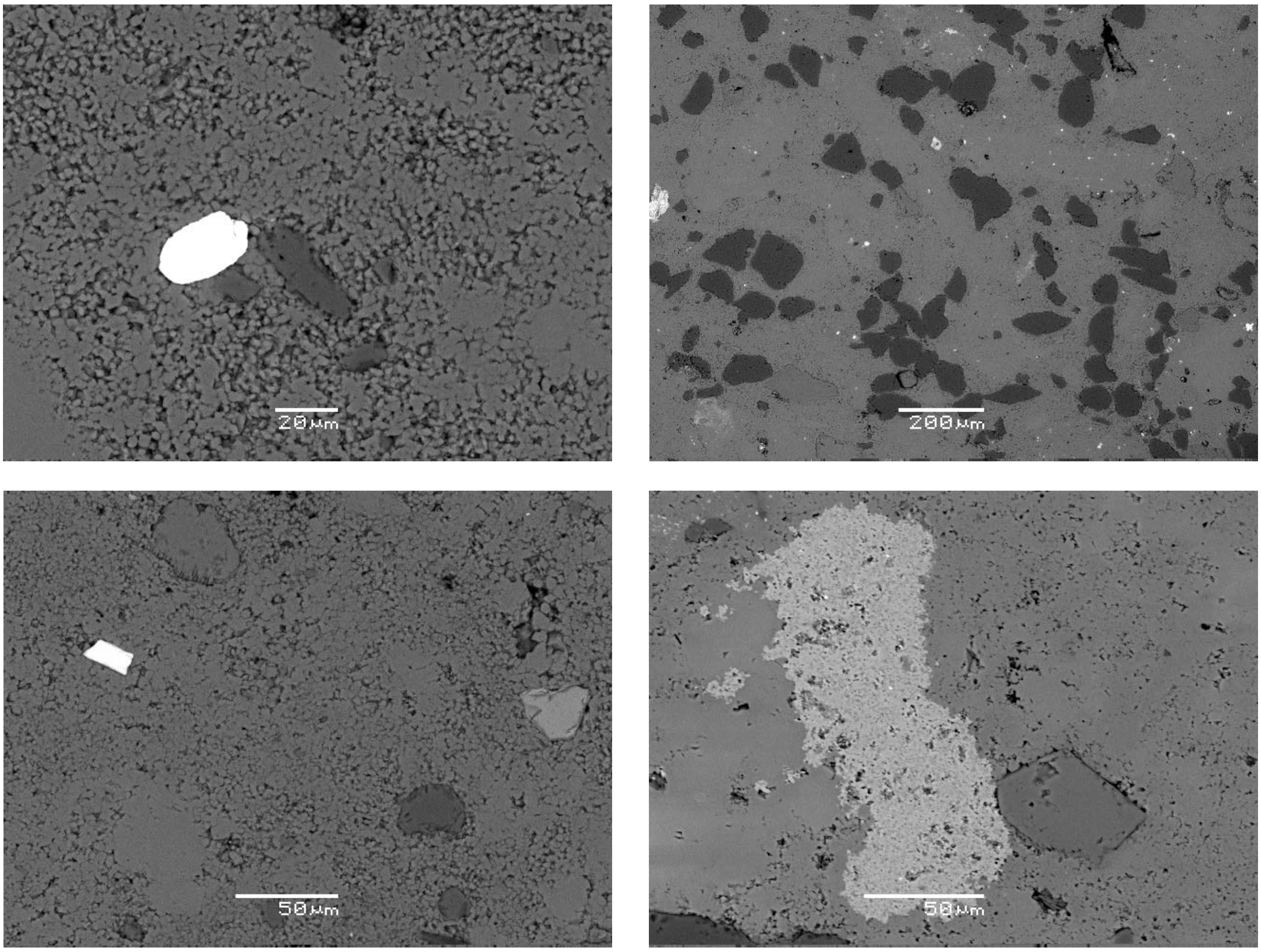

Fig. 2. High-resolution back-scattered electron (BSE) images of calcite with minor minerals disseminated in the calcite matrix of Minare limestone: a) Xenotime and quartz, b) quartz, c) zircon, epidote, feldspar, quartz, d) weathered apatite and feldspar.

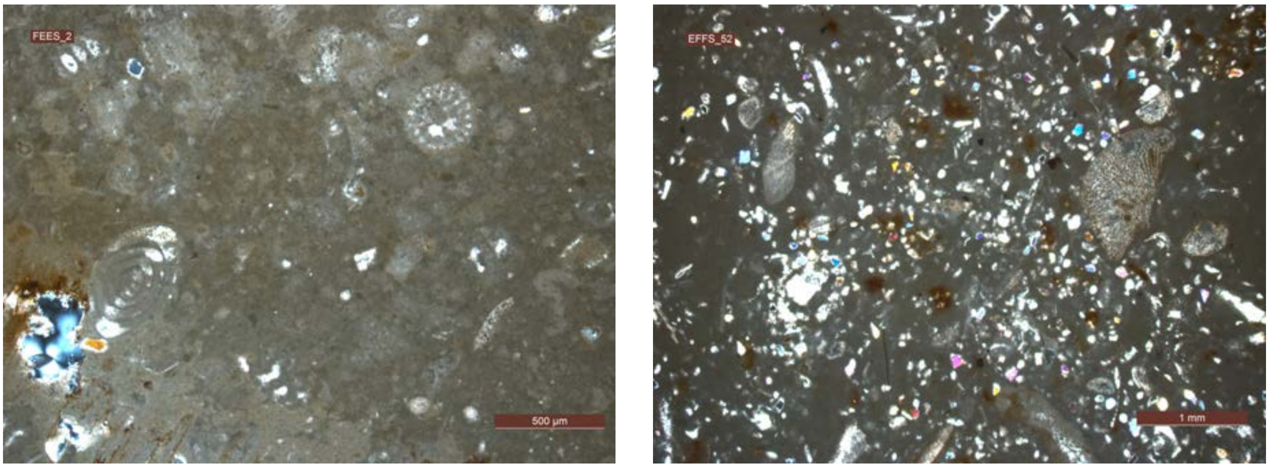

Fig. 3. Microfossils composed of calcified and lithified shells and corals in Minare limestone.

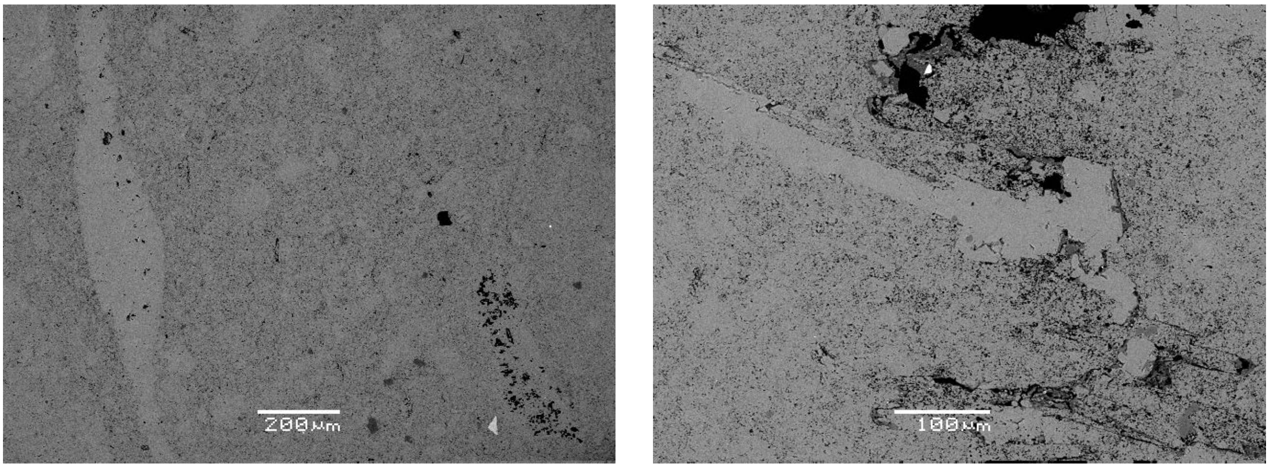

Fig. 4. Calcite veins and crystallized calcite along cracks and pores in Minare limestone.

presence of microfossils reveals that the rock is at least partly biological in origin (Fig. 3). Microveins and recrystallized calcite can be observed along fractures and pores (Fig. 4). Cracks could easily have formed during regional tectonic activity. Water has subsequently infiltrated the rock, dissolved some of the limestone and concentrated it in the cracks. The solution has gradually become saturated with calcium carbonate and crystallization has started from the surfaces adjoining the cracks, gradually filling them up.

According to XRD phase analyses, the Minare carbonate rock contains 68–99% calcite and 1–21% quartz, and in places considerable amounts of K-feldspar, kaolin, and kalsilite (Table 2).

Table 2. Mineral phases in Minare limestone and semi-quantitative values of their content (cc=calcite, qtz=quartz).

Sample no.	Mineral content
EFFS-2	cc 96%, qtz 4%
EFFS-52	cc 68%, qtz 21%, K-feldspar 11%
EFFS-3	cc 99%, qtz, 1%
EFFS-14	cc 83%, qtz 3%, kalsilite 14%
EFFS-14 (powder)	cc 78%, qtz 11%, kaolin 11%
EFFS-7	cc 98%, qtz, 2%

Table 3. Chemical composition (weight-%, determined by atomic absorption spectroscopy, AAS) of selected carbonate rock samples from Minare, Oromia.

Sample no.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI	Sr	sO_3
EFFS-3	<0.01	0.40	1.62	53.90	0.73	<0.01	0.24	0.01	<0.01	0.03	0.05	41.63	0.05	0.01
EFFS-7	0.98	0.44	1.22	53.54	0.68	<0.01	0.18	0.01	0.01	0.05	0.16	41.28	0.03	0.01
EFFS-14a	7.10	1.83	2.24	48.20	1.22	0.01	0.48	0.02	0.01	0.05	0.27	37.78	0.03	0.01
EFFS-14b	7.14	1.80	1.81	49.20	0.96	0.01	0.46	0.02	0.01	0.06	0.28	37.45	0.03	0.01
EFFS-52	<0.01	0.40	0.90	56.82	0.24	<0.01	0.24	0.01	0.15	0.03	0.05	41.11	0.02	<0.01

The results of chemical analyses of selected rock samples are presented in Table 3. Elevated silicon dioxide (SiO2) represents mainly quartz and feldspar, which corresponds to the XRD results and microscope observations. The relatively high aluminum oxide (Al2O3) and potassium oxide (K2O) content indicates the presence of clay in the form of weathered feldspar, kalsilite, and kaolin. The content of base metals is quite low. On average, the rock contains, in parts per million (ppm), Cu=21.4, Zn=15, Pb=0.6, Co=10.2, Ni=3, and Sr=30. Microscope studies confirmed that disseminated oxide and sulfide phases are responsible for these concentrations in the limestone. The small amounts of MgO in the rock might indicate the presence of Mg mainly in the calcite lattice, as also observed in the SEM analyses.

Although the mineralogical associations of trace and major elements are complex, SEM-EDS semi quantitative analyses indicate that Ca, Mg, and strontium (Sr) mainly occur in calcium carbonate (anhedral calcite). Manganese is mainly associated with Ti-Fe bearing minerals. Iron is found in carbonate minerals, oxides, and sulfides.

3.2 Moga marble, Benishangul Gumuz

Moga (also called Menta Wuha) marble is found in Benishangul Gumuz and partly in Amhara Regional State, some 330 km NW of Addis Ababa and 27 km SW of Chagni town. Moga marble occurs with interlayers of metasediments and metavolcanites (Chernet et al., unpublished). The marble is either rich in calcium carbonate (calcitic) or rich in magnesium carbonate (dolomitic). The calcitic marble usually shows a smooth, fresh weathering surface in outcrops and the color varies from pure white to light or dull grey. Outcrops of the dolomitic marble are more weathered, resulting in rough greyish or brownish surfaces. In places, both types of marble are interlayered and are generally fine-grained and only occasionally medium-grained.

In Moga marble, the calcite that formed the original limestone was recrystallized, forming granular to equigranular calcite crystals with distinct grain boundaries (Fig. 5a, b). Major minerals include calcite, dolomite, and quartz, with minor amounts of mica, Fe-oxides, Fe-Cu oxides, pyrite, apatite, zircon, rutile, barite, feldspar, and Zn-Cu sulfides. Quartz is occasionally interlocked with calcite grains and disseminated throughout the rock as a major mineral. Mica in the form of muscovite is rarely disseminated. The grain size of calcite crystals ranges from a few microns up to 3-4 mm. Continuous recrystallization is indicated by fine-grained calcite crystals developed along grain boundaries of larger crystals (Fig. 5b).

The dolomitic marble is characterized by a wide variation in grain size, from a few microns to about 4 mm. Due to the degree of metamorphism, Moga marble has no fossils or any original layering or bedding of the limestone. However, twinning is typical and characteristic of calcite and dolomite. Polysynthetic twinning in dolomite sedimentary rock is very rare. In Moga marble, the dolomite twinning is the result of pressure attributed to the formation of dolomitic marble (Fig. 6). There are some variations in the color and texture of the marble, from white to light and dark grey due to impurities, possibly mainly due to graphite inclusions.

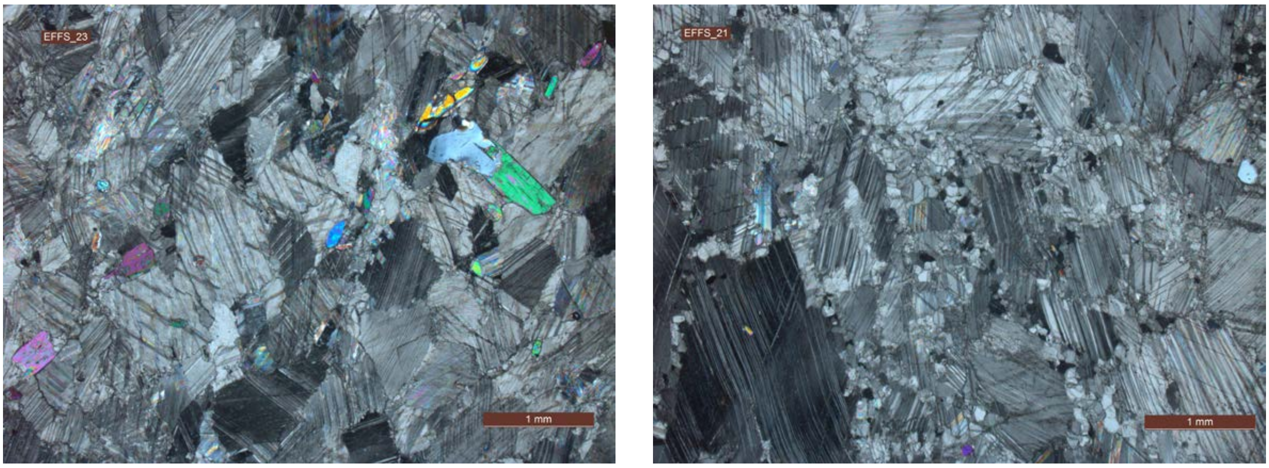

Fig. 5. a) Granular (equigranular) calcite with minor amounts of mica and quartz, and b) recrystallization of calcite mainly along grain boundaries of large crystals of calcite in Moga marble.

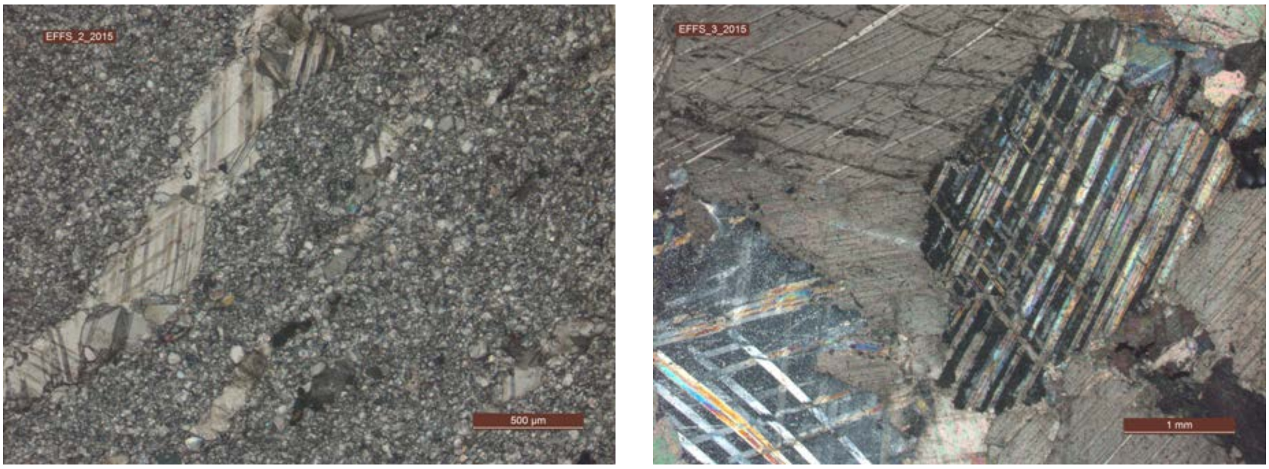

Fig. 6. a) Relatively fine-grained dolomitic Moga marble with calcite veinlets and disseminated grains, and b) coarse-grained (3-4 mm) large grains of dolomite with distinct twin lamellae.

In terms of mineral composition, the Moga marble deposit consists of calcitic and dolomitic marble types. This is clearly evident in the BSE images obtained with SEM (Fig. 7) and in phase analysis using the XRD technique (Table 4).

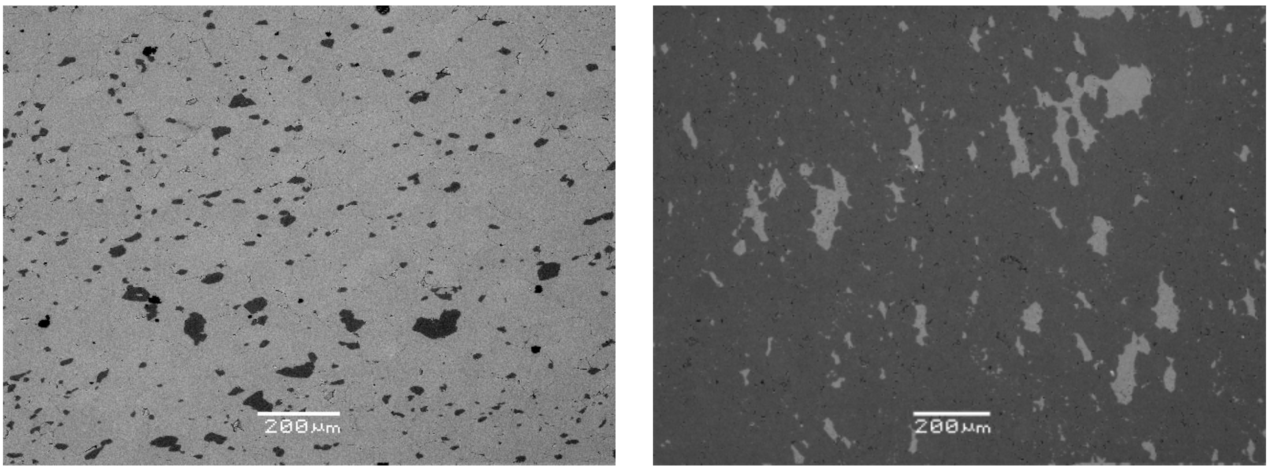

Fig. 7. a) Calcitic Moga marble with minor dolomite (dark) and b) dolomitic Moga marble with minor calcite (light grey).

Table 4. Results of X-ray diffraction (XRD) analyses of mineral phases in Moga marble and semi-quantitative values of their content (cc=calcite, dol=dolomite, qtz=quartz).

Sample no.	Mineral content
EFFS-21	cc 97%, qtz 3%
EFFS-23	cc 91%, qtz 2%, amphibole 7%
EFFS-39	cc 89%, dol 10%, qtz 1%
EFFS-47	cc 89%, qtz 5%, mica 6%
EFFS-3/15	cc 99%, qtz 1%
EFFS-2/15 light	dol 94%, cc 6%
EFFS-2/15 dark	dol 84%, cc 16%

The results of chemical analyses of selected samples are presented in Table 5. The SiO2 content mainly represents quartz, which corresponds to the XRD results and microscope observations. Base metal concentrations in Moga marble are relatively low, but higher than in the Minare limestone. On average, the rock contains, in ppm, Cu=70, Zn=27, Pb=7, Co=51, and Ni=3. Rarely disseminated oxide and sulfide phases might be responsible for the metal concentrations in the marble.

According to SEM-EDS analyses, Ca, Mg, Mn, and Sr are largely associated with the carbonates (calcite and dolomite). Iron is found not only in the carbonates, but also in oxides and sulphides, together with Zn, Cu, cobalt (Co), nickel (Ni), and lead (Pb).

Table 5. Chemical composition (weight-%, determined by atomic absorption spectroscopy, AAS) of selected rock samples of Moga marble.

sample no.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI	Sr	sO_3
EFFS-23	<0.01	0.01	0.64	54.18	1.62	0.01	0.24	0.01	<0.01	0.01	0.01	42.96	0.04	<0.01
EFFS-39	1.28	<0.01	0.20	34.99	18.98	<0.01	0.10	0.01	0.04	<0.01	0.03	42.98	0.05	0.01
EFFS-47	6.00	1.00	0.69	50.06	0.78	<0.01	0.56	0.05	0.02	0.03	0.05	40.00	0.06	0.01
EFFS-36	<0.01	0.10	0.91	53.72	0.70	<0.01	0.14	0.01	<0.01	0.03	0.08	42.99	0.03	<0.01
EFFS-21	<0.01	0.10	0.20	54.65	0.76	<0.01	0.12	0.01	0.01	0.02	0.07	42.41	0.02	0.01
MoM	0.48	0.50	<0.01	57.16	0.38	0.42	<0.01	<0.01	0.01	0.01	0.07	41.67		

4 TECHNICAL PROPERTIES OF MINARE LIMESTONE AND MOGA MARBLE

4.1 Agricultural lime production

Agricultural lime production is commonly a simple process that involves quarrying and/or mining limestone and/or dolomite and crushing/milling it to a lime. Agricultural lime is often produced as a co-product in operations designed to produce dimension stones, construction aggregate, quick lime, hydrated lime, cement, etc. However, there are some custom-built agricultural lime production sites and plants in countries where agriculture is one of the main contributors to the national economy. Although such plants run a much simpler production process, cost-effective (both for producers and consumers) and sustainable production should be practiced.

The influence of particle size distribution/fineness of agricultural lime on the rate of dissolution has been reviewed by a number of authors (e.g., Grafton 2010, Alvarez et al. 2010, Scott et al. 1992). The results indicate that the reactivity and agronomic effectiveness of lime largely depend on its fineness. It is therefore of critical importance that liming materials are milled to specified fineness levels to ensure realistic reactivity. Other factors being constant, the fineness has a very large bearing on the rapidity with which lime affects plant growth and soil pH. There are some variations in regulations controlling the fineness of grinding, but limes with a higher proportion of small fine material have greater capacity to dissolve, and therefore increase soil pH quickly (Scott et al. 1992).

For selected Moga marble and Minare limestone rock samples (Table 1), tests were performed to characterize the grindability of the rock in terms of ease of pulverization and energy consumption. The ideal/standard agricultural lime particle size distribution for small-scale farms prescribed by Mitchell et al. (1997) (i.e., 100% <2 mm, 60% <400 µm, 50% <150 µm) was taken as reference. The grindability index measurements were performed at GTK's Outokumpu pilot plant and bench scale processing laboratory, to compare ease of pulverization and determine the amount of energy required to produce agricultural lime with the given standard particle size distribution.

4.2 Grinding test procedure

The Bond Rod Mill Work Index (BRMWI) is a standard test for determining the net grinding energy requirement of a rock or ore sample (Bond 1961, Mosher & Tague 2001, Tavaresa et al. 2012). The BRMWI is a measure of the resistance of the material to crushing and grinding, which is the work index expressed as KWh/t. This index can be used to determine the grinding power required for a given throughput of material, in this case under rod mill grinding conditions. It is a 'locked cycle' dry grinding test conducted in a closed circuit attached to a laboratory screen. The closing screen size is determined based on the grinding fineness required. E.g., if the resulting product P80 =1 mm, the 'next bigger' √2 sieve size will be chosen as the closing screen (1 mm * √2 = 1.41 mm).

The standard BRMWI test procedure is first to stage-crush the sample to pass through a 12.5 mm screen, followed by screen analyses of the crushed feed material. For the grinding, the sample is packed into a 1250 mL cylinder using a vibrating table. The weight of the packed sample is the initial charge and is maintained throughout the test. The test then involves a series of batch grinds in a standard Bond rod mill. A Bond rod mill measures 305 mm by 610 mm, with wave liners and lifters, with the charge consisting of eight rods and weighing a total of 33.38 kg (Fig. 8).

For the first grinding period, the mill is run for an arbitrary number of revolutions. The sample is then screened on the selected closing screen size and any undersize material is replaced with fresh unsegregated feed to return the sample to the total initial weight. The number of revolutions is calculated from the results of the previous period, to produce sieve undersize equal to 1/2 of total charge of the mill. Grinding periods are continued until the net grams of sieve undersize produced per mill revolution reach equilibrium with 100% circulating load. After equilibrium is reached repeatedly, the last three undersize products are combined and screen-analyzed. The average of the last three net

Fig. 8. Bond rod mill grinding machine and mill charges of two different sizes.

grams per revolution determines the rod mill grindability (G_{rp}) in g/rev. The work index is calculated using the Bond equation (eq. 1):

$$W_i = \frac{68,4}{P_i^{0,23} * G_{rp}^{0,625} * \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)} \quad (1)$$

Where:
P_i closing sieve size in microns
G_{rp} grindability value for rod mills, net grams of mill product passing sieve size P_i produced per mill revolution
P_{80} required product size in microns at which 80% passes
F_{80} feed size in microns at which 80% passes.

4.3 Grinding test result

The Minare and Moga rock samples were stage-crushed to 100% passing the 12.5 mm screen and analyzed. The particle size distribution of the feed samples for the Bond rod mill test is given in Table 6. The samples were packed in a 1250-mL cylinder, which was the initial rock charge maintained throughout the test.

The ideal agricultural lime is considered to be a ground carbonate rock with particle size distribution of 100% <2 mm, 60% <400 µm and up to 50% <150 µm (Mitchell et al. 1997, 1998). A "closing screen size" (Pi) =1.4 mm was chosen according to the particle size distribution of the ideal agricultural lime (P80 = 1 mm).

Table 6. Particle size distribution of the rod mill feed from the Moga marble and Minare limestone samples.

Particle size (µm)	Weight (g)	Passing (g)	Wt (%)	Weight (g)	Passing (g)	Wt (%)
	Marble (Moga)			Limestone (Minare)		
12500	0.0	100.0	0.0	0.0	100.0	0.0
10000	186.2	82.6	17.4	180.2	81.4	18.6
8000	212.8	62.7	19.9	171.6	63.7	17.7
5600	204.9	43.6	19.1	204.2	42.6	21.1
4000	91.5	35.1	8.5	96.4	32.7	9.9
2800	79.5	27.7	7.4	88.7	23.5	9.2
2000	46.3	23.3	4.3	55.0	17.9	5.7
1400	41.7	19.4	3.9	46.5	13.1	4.8
1000	29.5	16.7	2.8	30.3	9.9	3.1
710	26.4	14.2	2.5	25.0	7.4	2.6
500	20.6	12.3	1.9	17.7	5.5	1.8
250	35.6	9.0	3.3	23.7	3.1	2.4
125	36.1	5.6	3.4	15.5	1.5	1.6
90	14.9	4.2	1.4	5.3	0.9	0.5
75	11.2	3.2	1.0	2.5	0.7	0.3
-75	33.9		3.2	6.7		0.7
Total	1071.1		100	969.3		100

After preparing the initial feed, the Bond rod mill test was performed and the BRMWI value was determined to be 8.8kWh/t for the Moga marble sample and 15.3kWh/t for the Minare limestone sample. The particle size distribution of the product and the resulting standard agricultural lime fineness are given in Table 7 and Figure 9.

Table 7. Particle size distribution of the rod mill product from the Moga marble and Minare limestone samples.

Particle size (µm)	Weight (g)	Passing (g)	Wt (%)		Weight (g)	Passing (g)	Wt (%)
Marble (Moga)					Limestone (Minare)		
1400	0.0	100.0	0.0		0.0	100.0	0.0
1000	21.6	80.2	19.8		23.6	76.1	23.9
710	16.9	64.7	15.5		19.6	56.2	19.9
500	11.6	54.1	10.6		12.8	43.2	13.0
250	17.5	38.0	16.0		17.0	26.0	17.2
125	15.6	23.7	14.3		12.4	13.4	12.6
90	6.3	18.0	5.8		5.3	8.0	5.4
75	3.9	14.4	3.6		2.2	5.8	2.2
-75	15.7		14.4		5.7		5.8
Total	109.1		100		98.6		100

Limestone is a sedimentary rock widely regarded as a soft rock. Marble, on the other hand, is a recrystallized form of limestone and is generally considered to be a hard rock that is commonly used as a building material. However, the present comminution tests revealed that grinding Moga calcitic and dolomitic marble down to a standard agricultural lime requires only half the energy (8.8kWh/t) compared with producing standard agricultural lime from Minare limestone (15.3 kWh/t). The main results are given in Table 8 and Figure 9.

Table 8. Main results of the Bond rod mill tests for the Moga marble and Minare limestone samples.

Bond rod mill test	Marble	Limestone
Product in the feed	19.4%	13.1%
Bulk density	1888 g/dm^3	1716 g/dm^3
Ideal potential product	1179.7 g	1072.2 g
Average equilibrium load	99%	100%
Average product	21.700 g/rev	9.639 g/rev
80% passing feed size	9737 µm	9841 µm
80% passing product size	996 µm	1066 µm
Bond Rod Mill Work Index (kWh/t)	8.8 kWh/t	15.3 kWh/t

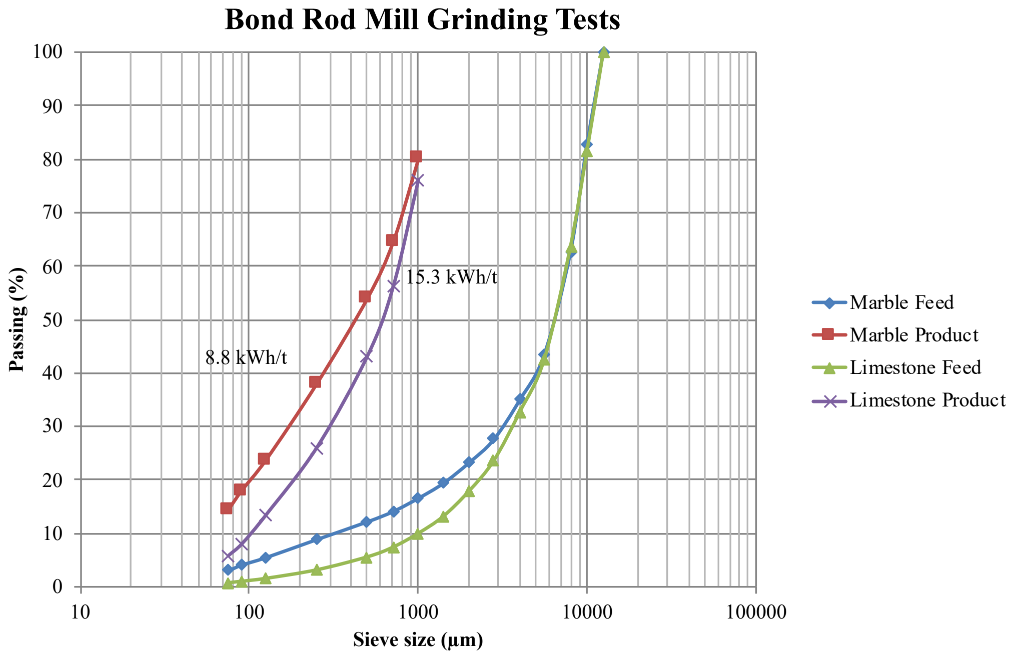

Fig. 9. Cumulative particle size curves for feed and products of Moga marble and Minare limestone.

The tests clearly indicate that grindability largely depends on the mineralogical characteristics of the rock. Mineral composition, grain size distribution, grain boundaries, and microdiscontinuities (e.g., porosity, fractures, twinnings, etc.) increase the surface area, which will affect the grinding performance. For a description of the mineralogy of Moga marble and Minare limestone, see sections 3.1 and 3.2 of this paper. Mechanical fragmentation of the marble required less energy because of the pre-existing grain boundaries and crystal discontinuities (including fractures and pores) created by the crystallization and recrystallization processes (Fig. 10).

According to the test results and JKTech classification, the Moga marble sample can be classified as a soft material and the Minare limestone sample as a hard material (Table 9). JKTech Pty Ltd is the technology transfer company for the Sustainable Minerals Institute (SMI) at The University of Queensland (UQ).

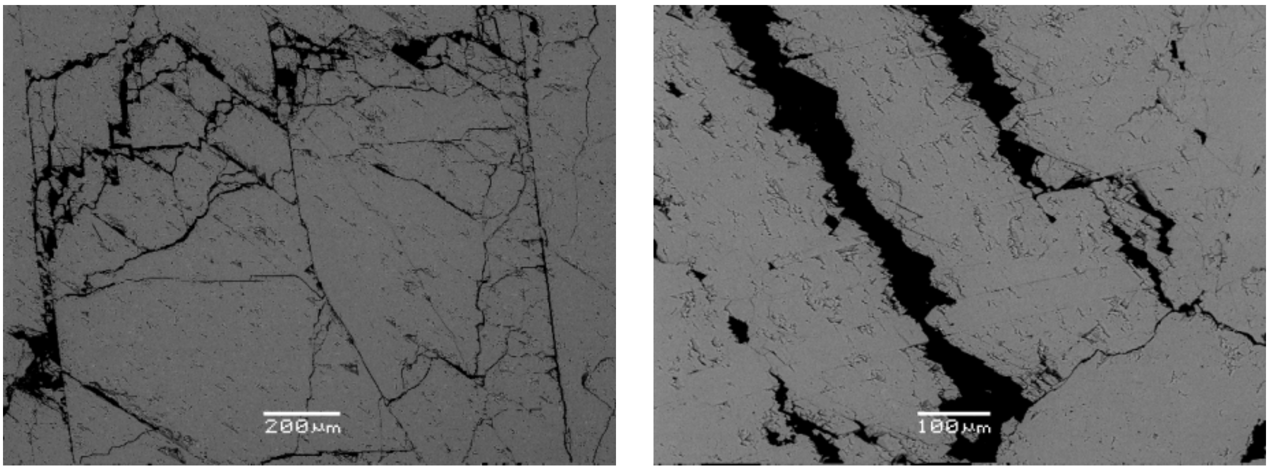

Fig. 10. Fractures and pore spaces in dolomitic Moga marble.

Table 9. JKTech classification of hardness of a material based on its Bond Rod Mill Work Index (BRMWI).

Property	Soft	Medium	Hard	Very hard
BRMWI (kWh/t)	7–9	9–14	14–20	>20

5 CONCLUSIONS

There is an urgent need for improved food security in Ethiopia, and increasing agricultural production is a vital measure for tackling this challenge. However, little attention has been paid to the quality of Ethiopian soils and especially their acidity, although it is well known that large areas of the country's territory are affected by severe acidity and that growing crops on acidic soils gives poor yields.

The quality of the soils can be improved by reducing their acidity. In this context, the use of agricultural lime is important and its availability and quality are major issues. Given increasing demand, the most important task for decision makers in the agricultural sector and related industries is to ensure the availability of high-quality agricultural lime. The main quality criteria with regard to a lime resource are the neutralizing value (a measure of purity), particle size (fineness of the product), and crushability (ease of pulverization). All these parameters are determined by the chemical and the physical properties of the available rock resource. In this study, these properties were examined and documented for two selected potential lime resources in Ethiopia: Minare limestone (Oromia region) and Moga marble (Benishangul Gumuz).

The composition of Minare limestone is dominated by calcite (calcite 68–99 wt. %, CaO up to 54 wt. %, MgO max. 1 wt. %), with a variable amount of silicates and a small amount of oxides and sulfides. Minare limestone is a huge resource for agricultural lime and lies close to acid-affected cultivated and pastoral lands. However, the resource is poor in Mg and could best be used for soils not deficient in magnesium. The Moga carbonate resource, on the other hand, is a metamorphic equivalent called marble, which is both calcitic (calcite 89–97 wt. %, CaO up to 57 wt. %) and dolomitic (dolomite 84–94 wt. %, MgO up to 19 wt. %) in composition. The Moga resources could easily be used as agricultural lime, to improve the surrounding unproductive acid soils.

Grindability tests for producing standard agricultural lime revealed that the energy requirement was lower for Moga marble (about 8.8 kWh/t) than for Minare limestone (about 15.3 kWh/t). These results clearly indicate that, apart from geological and mineralogical studies, comminution tests are necessary before setting up production sites and installing crushing facilities.

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