Construction raw materials in Timor Leste and sustainable development

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Abstract: Timor Leste is the newest and one of the poorer nations in the world. One of its main challenges that could lead to poverty reduction is the reconstruction and maintenance of the infrastructures that were almost completely destroyed after its independence referendum. To achieve this, there is an imperative need for construction raw materials in a country where the extractive industry is scarce and artisanal. Available geological studies deal with the island's geology and tectonic evolution or its oil and gas potentialities. Very few broach other geological resources. A general study of the country's territory demonstrates that Timor Leste possesses large resources in clays, limestones and sand and gravel, which can support small- to large-scale raw material extractive industries. Some selected areas have been the target of more detailed study: Venilale and Aileu, with resources for structural ceramics and whiteware respectively, and Beheda, where a crinoid-rich limestone crops out, with potential for usage as ornamental stone. These resources are suitable for non-sophisticated small-scale mining operations that should be able to accomplish environmental and social liabilities. No public policy exists for the management of these mineral resources, which is essential for the sustainable development of Timor Leste.

Timor Leste is a newly independent country on the eastern part of the island of Timor that is located on the border of the Lesser Sunda archipelago (Indonesia). It has an area of about 15 000 km^2, which includes two islands, Atauro and Jaco, and the enclave of Oecussi located on the north coast of Western Timor. The country's capital, located on the north coast, is Dili. The Timor Sea separates the island from Australia (Fig. 1).

The territory is about 275 km long and 100 km at its greatest width, and is characterized by a varied morphology and ecology. A central range of hills and mountains, up to 3000 m, divides the country's northern region from the southern one. The climate is tropical, with distinct rainy and dry seasons. The natural combination of heavy rainfall during the rainy season (November to April) and a terrain morphology with slopes of around 40% occurring in approximately half of the territory's area, can result in a range of natural hazards (mainly floods, landslides and soil erosion).

The first known geological study is reported by Hirschi (1907). However, it was not until the post-World War II period that important regional studies were carried out, mainly on behalf of oil industry interests (Grunau 1953, 1956, 1957; Wanner 1956; Gageonnet & Lemoine 1957, 1958; Leme & Coelho 1962; Leme 1963, 1968). Several of these geological studies included mapping at different scales, but it was Audley-Charles (1968) who first produced a regional geological map of Timor Leste (scale 1:250 000) and formalized previous work into the presently recognized stratigraphy of the country. This map (Fig. 2) remains the main geological reference of Timor Leste. Geological research undertaken in Timor Leste by the University of London, Southeast Asia Research Group, was interrupted by Indonesian annexation. During this period, little geological fieldwork was carried out, except for that by Harris and his co-workers (Harris 1991; Prasetyadi & Harris 1996; Reed *et al.* 1996; Harris *et al.* 1998) and by the Indonesian Geological Research and Development Centre, which published the Dili and Baucau geological map sheets of Timor Leste at 1:250 000 scale (Bachri & Situmorang 1994; Partoyo *et al.* 1995). In recent years, significant geological studies have been carried out in eastern Timor (Harris & Long 2000; Charlton 2001, 2002; Charlton *et al.* 2002), mostly concerning its tectonic evolution and implications for oil exploration. Nevertheless, the geological knowledge of Timor Leste is incomplete, particularly in respect to its mineral resources.

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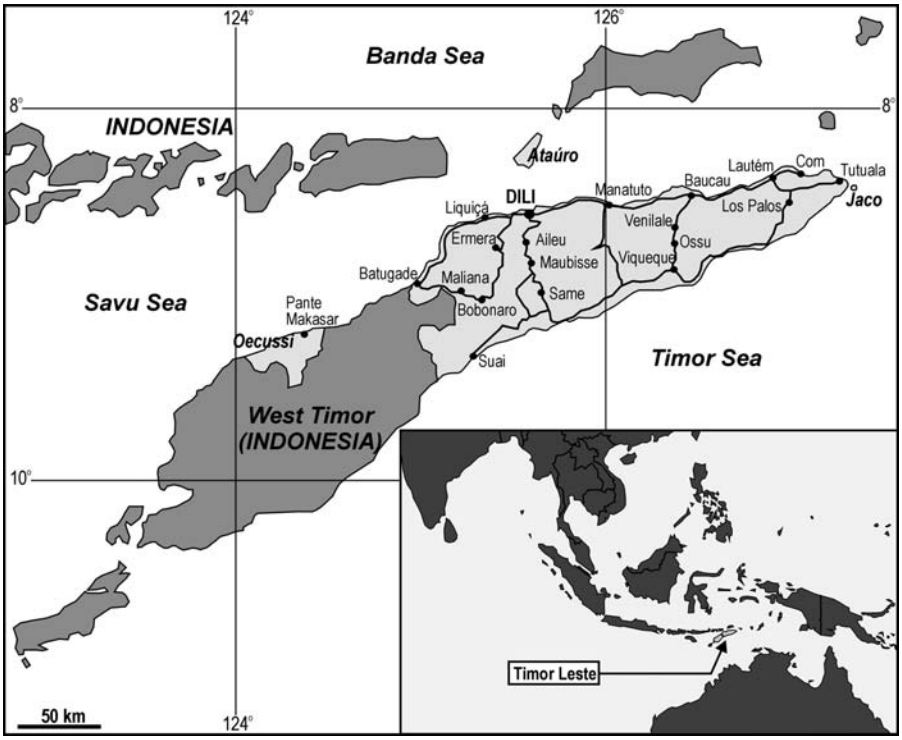

Fig. 1. Map showing location of Timor Leste.

Timor is a non-volcanic island with a complex geological history and is not yet well understood in the evolutionary context of the boundary between Asian and Australian tectonic plates. According to the recent studies, Timor represents a contractional wedge formed by mechanical accretion of underthrusted Australian continental-margin cover sequences that represent autochthonous, parauthochthonous, allochthonous and syn-orogenic olistrostrome units (Audley-Charles 1968; Charlton *et al.* 1991; Harris 1991, Harris & Long 2000; Charlton 2002).

The economic and social infrastructure of Timor Leste was severely damaged as a result of the devastating conflict that occurred after the independence referendum of 1999. International support was coordinated by the United Nations agencies in Timor Leste in order to restore peace and security, but also to help with reconstruction and economic revival. In this context, one of the contributions of the Portuguese Government was a preliminary assessment of the non-metallic mineral resources of Timor Leste, which is the basis of the results presented here.

Timor Leste's development will undoubtedly require the use of its natural resources. A key challenge for this new nation is how to develop it within the principles of sustainable development, thus contributing to the improvement of the well-being of the Timorese people.

The development strategy of Timor Leste

Timor Leste is one of the poorest countries in the world, with a per capita income lower than US$1 a day (UNDP 2000). This situation has a historical background that started with the settlement of a Portuguese trading post in 1562, the ensuing colonization period and later Indonesian military occupation after 1975. During the 500 years of colonization and foreign occupation, the economic structure was based on the exploitation of Timor Leste's natural resources, for short-term profits without a sustainable economic policy (Sandlund *et al.* 2001). The main commodities that were exploited included sandalwood, honey and bees wax. Since the beginning of the 20th century, a more sustainable policy led to a few phases of agricultural development based on coffee production (UNDP 2002). During Indonesian occupation, Timor Leste's fragile economy became increasingly based on urban

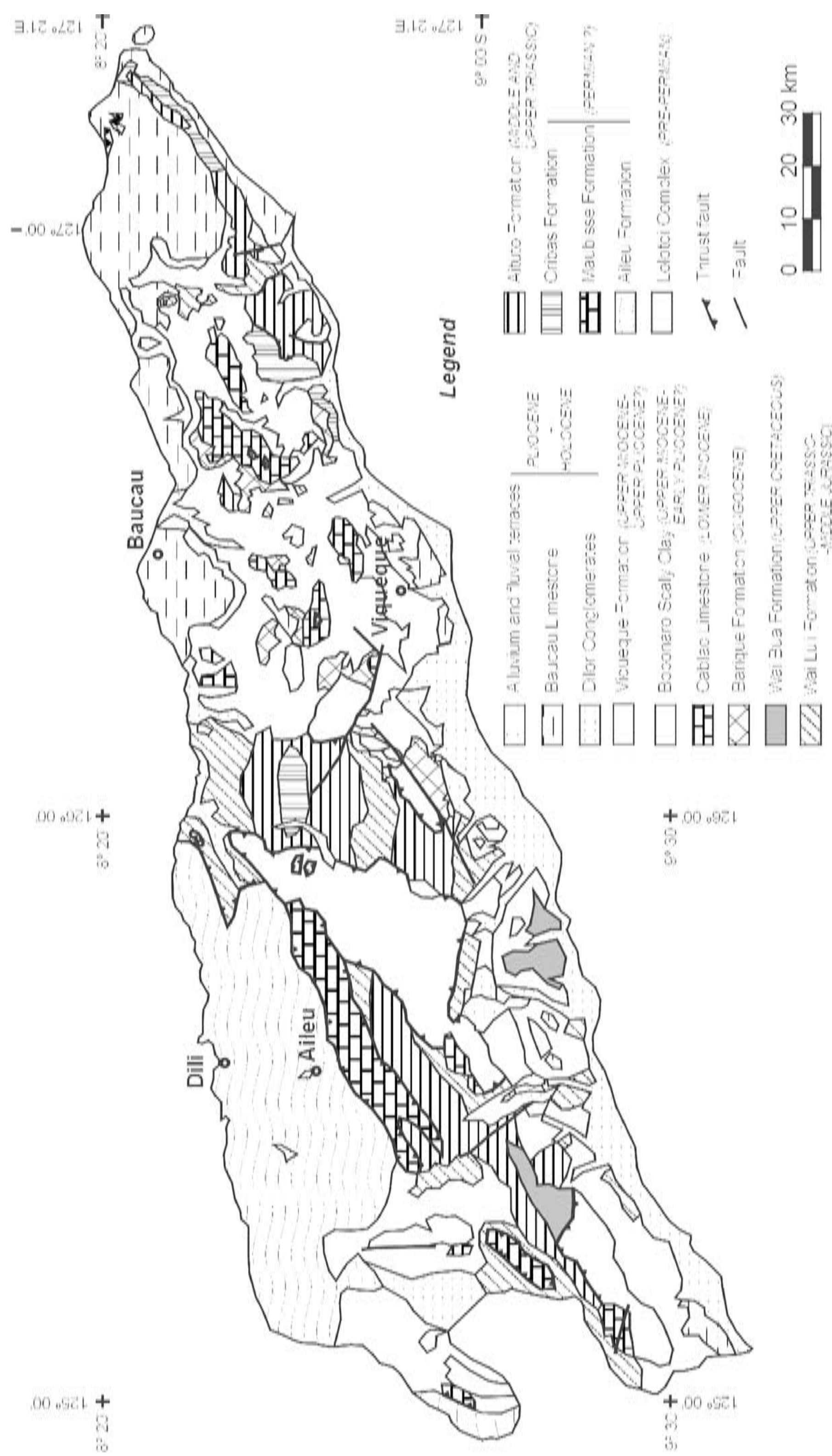

Fig. 2. Simplified geological map of Timor Leste (modified from Audley-Charles 1968).

services, resulting in an economic downturn in the contribution of agriculture to GDP from 60% in 1981 to about 25% in 1998 (UNDP 2002). Other economic activities such as furniture manufacturing and mining remained largely undeveloped.

The tragic and violent conflicts carried out by the Indonesian troops and anti-independence militias after the independence referendum in 1999 caused great changes in population settlement patterns, agricultural production and other microeconomic activities. Approximately 70% of all houses and infrastructure were destroyed and 75% of the entire population was displaced (UNDP 2000; Sandlund *et al.* 2001). Around one-quarter of the 28 000 civil servants in pre-conflict times were non-Timorese, occupying the top administrative positions. Their exit left the territory lacking skilled human resources (UNDP 2002).

According to statistical data provided in UNDP (2000, 2002) reports, Timor Leste's present-day population of about one million people is very young (48% below the age of 17 years), and is growing at a rate of 2.5%. More than three-quarters of the population live in rural areas from subsistence agriculture without access to basic social services such as drinking water, electricity, and health and sanitation services. Official unemployment figures indicate that 16% of the population are out of work, but according to CIA's World Fact Book (WFB 2004), this figure is closer to 50%. Half of the Timorese people are unable to read or write.

At present, Timor Leste's exports are almost totally linked to coffee, which is currently being reestablished. This situation is expected to change shortly, with revenues from the exploitation of oil and gas resources in the Timor Sea. Most commodities, from cooking oil to cement, have to be imported, which is the reason why the future of Timor Leste depends on present international support.

Timor Leste became an independent and internationally recognized new nation in May 2002. Its government presented a strategic plan regarding the nation's development – the National Development Plan (NDP 2002) – with two main goals: poverty reduction and sustainable economic growth. The Plan is heavily focused on the sustainable development principles advocated on United Nation's Agenda 21 and the Johannesburg's World Summit on Sustainable Development.

In connection to the Millennium development goals, a policy for poverty reduction is outlined based on a fast but sustainable economic growth supported not only by future oil and gas revenues, but also by the exploitation of economic opportunities based on the use of other resources, such as agriculture, fisheries and forestry. Agriculture is highlighted as a key growth area, especially if productivity improvements are achieved within small-scale agro-units.

Timor Leste' strategy on mineral resources

The NDP's outlined strategy for mineral resources in Timor Leste is mainly described in a report entitled 'Natural and Mineral Resources Inventory, Policy and Development Strategy for East Timor', which was prepared by the United Nations agency ESCAP (Economic and Social Commission for Asia and the Pacific). It is published as 'Exploring Timor-Leste – Mineral and Hydrocarbon Potential' (ESCAP 2002). This important document presents a draft legal framework regarding the management of Timor Leste's mineral resources. In addition, it provides an overview of the general characterization of the resources and their potential, based on known mineral occurrences. Special emphasis is given to resources that can yield important economic revenues, such as onshore oil & gas, chromite, copper and gold. To ensure a sustainable framework for mineral development, the priorities addressed in the NDP of Timor Leste's Government are:

- the establishment of a legal framework and an institutional capacity building programme for medium- to long-term management of the mining sector; and
- the creation of investment opportunities.

The Government has identified one of the short-term paths to economic growth and consequent poverty reduction as the infrastructure reconstruction maintenance development. The NDP states that an effective physical infrastructure system is crucial for agricultural productivity, business investment, and is instrumental to human development. Industrial minerals play a key role in this development, providing raw materials essential for construction, such as aggregates and common clays for bricks and roof tiles manufacturing. However, the importance of these mineral resources, namely with respect to resource availability, accessibility and environmental sustainability, is stated neither in the government's NDP, nor in the several strategic documents that have been published by United Nations agencies dealing with Timor Leste development, such as 'Building Blocks for a Nation' (UNDP 2000) and 'Timor-Leste: Programme Package

Document for Sustainable Human Development' (UNDP 2003). One of the most important documents is 'The Democratic Republic of Timor Leste – Public Expenditure Review' (World Bank 2004), where several pages address the needs and economic assessment of road reconstruction and maintenance without mentioning raw materials requirements. This view, that construction mineral resources 'come from heaven', is not just a Timor Leste problem, but is common worldwide (Perez 2001; Wellmer & Becker-Platen 2002; Cárdenas & Chaparro 2004) and fails to embrace the fundamental concepts of sustainable development.

Construction raw materials in Timor Leste

Timor Leste's geology is characterized by considerable lithological diversity, favourable for the occurrence of a wide variety of mineral resources. Nevertheless, taking into account the immediate infrastructure reconstruction and development needs, attention is focused on construction raw materials, and particularly on the identification of target sites that in the short term can support the supply of these raw materials. Table 1 summarizes the results of a regional geological field survey supported by the mapping of Audley-Charles (1968) and presents the mineral resource potential of Timor Leste. All the geological units referred to from this point forward were defined by Audley-Charles (1968), unless otherwise mentioned.

Old and present-day mining activities represent the best evidence for mineral potential. Mining activity in Timor Leste has always been very incipient. Evidence of old exploitations found in Timor Leste comprise the following.

- Alluvium clays exploitation in the Dili's Fatumeta quarter, where a small deactivated two-kiln brick- and tile-making plant still stands. Nowadays, bricks and tiles are sporadically produced there by artisanal means, being fired in holes that are used as kilns.
- Brick- and tile-making plant near Aileu town, which has never worked due to the 1999 conflict; it was intended to use whitish clayey raw material, which crops out in the surrounding area.
- Inactive exploitation of marble boulders in a colluvium deposit in the Manatuto district, 40 km east of Dili, for ornamental purposes.
- An inactive kiln in Balibo (Maliana district) village, about 70 km southwest of Dili, where coral reef debris was used for lime production.

The present-day mining activity is limited to:

- sand and gravel extraction for road and building construction exploited by artisanal means in flat downstream areas of the main rivers;
- small artisanal limestone crushing plant and a modern quarry and stone crushing plant, managed by a private company near Dili, where intrusive igneous basic rocks are exploited;
- clay-rich material from alluvium deposits used countrywide for the manufacture of sun-dried bricks.

Ceramic raw materials

Brick- and tile-making plants can be of major importance for the reconstruction needs and further development of Timor Leste. The use of indigenous construction materials can replace uneconomic practices, such as the present-day use of heavy cement bricks made with imported cement and imported zinc plates used for climatically inappropriate roofing purposes. The industry would also create much needed job opportunities and provide training of skilled human resources.

Critical to the development of a ceramic industry in Timor Leste is an assessment of the country's potential for ceramic raw materials, in particular, common clays. This assessment must ensure that the lithologies are of suitable quality, uniformity and thickness and are free of major tectonic disturbances, in addition to having a favourable location in relation to consumer centres and accessibility.

Potential lithostratigraphical units for the supply of ceramic raw materials, in order of importance, are the Bobonaro Scaly Clay, Aileu Formation, Suai Formation and Ainaro Gravels (Table 1).

The Bobonaro Scaly Clay (Audley-Charles 1965), the Bobonaro Complex (Rosidi *et al.* 1979) or the Bobonaro Mélange (Harris *et al.* 1998) are all different names for a clay-rich unit, which is widespread all over the Timor Leste's territory, covering about 60% of its area. This unit is a tectonic/sedimentary mélange of Upper Miocene to Early Pliocene age (Audley-Charles 1968; Harris *et al.* 1998), with considerable lithological uniformity. It consists of a clay matrix in which unsorted blocks from structurally and stratigraphically overlying units are found. The clays vary widely in colour, but commonly have a distinctive scaly clay fabric. Clay mineralogy varies throughout the unit, but two main mineral assemblages occur: illite and smectite, and illite, kaolinite and chlorite (Harris *et al.* 1998).

Table 1. *Exploitable non-metallic raw materials and their potential application*

Formation*	Age	Thickness (m)	Lithology	Raw Material	Possible application
Suai Formation	Holocene and Pleistocene	1000	Unconsolidated rudites and arenites ranging from fine silts to pebbly gravels	Aggregates, common clays	Building industry, ceramics industry
Poros Limestone	Holocene and Pleistocene	20	Pale-brown to cream limestone that weathers grey. It is hard, thin bedded and rich in lacustrine gastropods and algae	–	–
Baucau Limestone	Holocene and Pleistocene	100	Hard, cavernous, massive white coral-reef limestone, weathers to a pale grey colour	Biocalciclastic limestone	Chemical industry, lime
Ainaro Gravels	Pliocene to Holocene	100 (?)	Stranded alluvium terraces	Kaolin, aggregates, common clays	Building industry, ceramics industry
Dilor Conglomerate	Upper Miocene to Upper Pliocene	300	Poorly sorted sandy conglomerate with a dark red lateritic crust	–	–
Lari Guti Limestone	Upper Miocene to Upper Pliocene	75	Sequence of yellow calcarenites and thin coral reef rocks	Biocalciclastic limestone	Chemical industry, lime
Viqueque Formation	Upper Miocene to Upper Pliocene	800	Massive white marl and grey claystone interbedded with a few chalky limestones; siltstones and sandstones upwards	Marls, micritic limestones	Cement industry, chemical industry (?)
Bobonaro Scaly Clay	Upper Miocene to Early Pliocene (?)	>2000	Soft and variegated scaly clay with exotic blocks and lenses of rocks of all ages and sizes in it; clay matrix colour varies much, but predominantly grey	Common and special clays (specially bentonitic (?) clays)	Ceramics industry, chemical industry (?)
Cablac Limestone	Lower Miocene	600	Hard, massive limestones of several types: calcilutites, oolitic limestone, calcarenite and intraformational conglomerate	Limestone (sparry, micritic, brecciated), aggregates	Ornamental stone industry, building industry
Barique Formation	Oligocene	300	Basic tuffs (fragments of basalts and serpentinites), feldspathic dacitic tuffs, alteration usually severe; minor interbedded foraminiferal quartz-sandstones. Andesites with zoned feldspars are common	–	–

Dartollu Limestone	Middle and Upper Eocene	100	Thick bedded, brown biocalcarenites containing carbonate algae and foraminifera or echinoderm fragments and foraminifera	Limestone (sparry, micritic, brecciated), aggregates	Ornamental stone industry (?), building industry
Seical Formation	Middle Eocene and Lower Cretaceous	100	Radiolarites, radiolarian shales, cherts and marls	Radiolarites	Chemical industry, abrasives, filters, absorbents
Borolalo Limestone	Maestrichtian to Campanian	200	Thickly bedded calcilutites; cherts occur as red or black nodules or veins	Micritic limestone, aggregates	Ornamental stone industry (?), building industry
Wai Bua Formation	Maestrichtian to Aptian	500	Radiolarian marls and shales, bedded coloured cherts, radiolarites, biocalcarenites	Radiolarites	Chemical industry, abrasives, filters, absorbents
Wai Luli Formation	Upper Triassic to Middle Jurassic	1000	Marls, calcilutites, micaceous shales and quartz arenites; basal units spotted blue-grey marls and calcilutites bearing ammonites	Marls, micritic limestones bearing ammonites	Cement industry (?)
Aitutu Formation	Norian to Ladinian	1000	Radiolarian calcilutites, shales and carbonate-rich shales and sandstones	–	–
Cribas Formation	Upper Permian	500	Shales, micaceous shales, silty shales with carbonate and clay-ironstone nodules	–	–
Atahoc Formation	Lower Permian	600	Black pyritic shales, silty-shales, quartz sandstones calcilutites and carbonate nodules	–	–
Maubisse Formation	Permian	900	Well-bedded limestones (biocalcarenites) and massive reefs; limestones are coloured red, pink, white and grey and very rich in reef fauna and debris. Interbedded conglomerates contain clasts of eruptive rocks and tuff	Limestone (sparry, micritic, brecciated), aggregates	Ornamental stone industry, building industry, lime
Aileu Formation	Permian (?)	>1000	Light-coloured shales, phyllites, slates, igneous rocks; in the north coast schists, volcanics, amphibolites, serpentinites and diorite	Marble, kaolin, common clays, igneous aggregates (andesite, basalt, gabbro)	Ornamental stone industry, ceramics industry, building industry
Lolotoi Complex	Pre-Permian (?)	1300 (?)	Quartz-mica-phyllites, quartz-mica-schists, black schists with quartz; metagabbro, dolerite and gneiss, strongly fractured are also present	Igneous aggregates (gabbro, gneiss, quartzite, dolerite)	Building industry

*Main lithostratigraphical units in East Timor as defined by Audley-Charles (1968).

The Aileu Formation or Aileu Metamorphic Complex (Charlton 2002) occupies a single large massif in northwestern Timor Leste, consisting of a sequence of deformed and metamorphosed pelitic, psammitic, basic and carbonate-rich rocks. Earlier studies suggested a Permian age for the metasedimentary sequence (Gageonnet & Lemoine 1958; Leme 1968), but Mesozoic fossils have been reported (Brunnschweiler 1977; Harris & Long 2000; Charlton 2002). In the southwest, clay alteration of argillaceous schist has produced ceramic-grade material.

The Suai Formation and the Ainaro Gravels are Quaternary (Audley-Charles 1968) thick coastal unconsolidated sediments, including alluvium deposits, and stranded alluvial terraces, respectively.

Geological mapping and preliminary characterization of the raw materials were carried out in two areas, Venilale and Aileu, representing target sites where ceramic raw material can be provided in the short term.

Venilale clayey deposits

In the Venilale area, 25 km south of Baucau (the second largest city in Timor Leste) the Bobonaro Scaly Clay occurs in extensive and massive outcrops. In the area under investigation (Fig. 3), fresh exposures of clayey deposits were identified (Fig. 4a). These clays are consistently soft with a variegated colour and frequently display a scaly texture (Fig. 4b). The predominant colour is light grey to dark reddish-brown and dark olive-green. Fragments of exotic blocks occur embedded in the clay matrix, chaotically distributed and randomly orientated, with a size range from a few millimetres to 60 cm in diameter. Its nature is highly variable, although reddish and brown cherts, probably related to the Wai Bua Formation, prevail. Other exotic material found in the area includes shale fragments, probably from the Wai Luli Formation and, less frequently, crinoid-rich Permian limestones of Maubisse Formation.

Three channel samples were collected, representative of the prevailing clayey facies found in the study area. All three samples consist of fine-grained sediments falling in three distinct fields of the Shepard's diagram (Fig. 5; Shepard 1954): clay, silty clay and clayey silt. On the basis of their granulometry, these materials may be adequate for the manufacture of structural clay products,

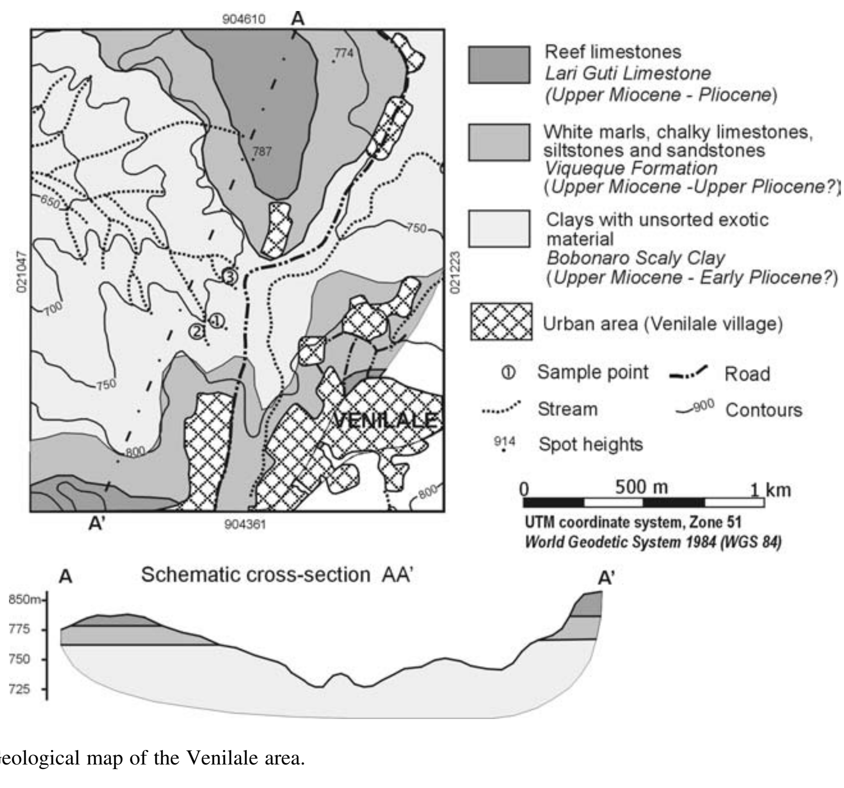

Fig. 3. Geological map of the Venilale area.

(a)

(b)

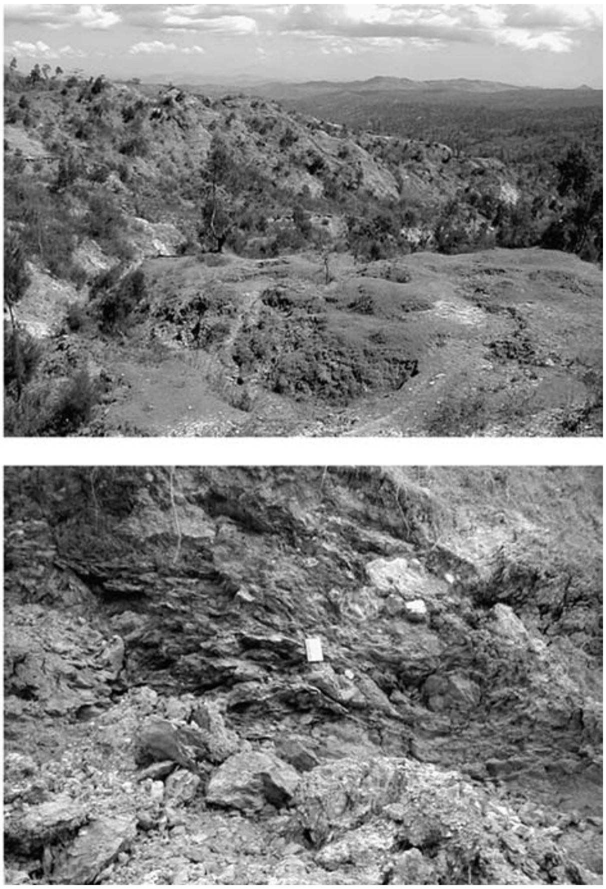

Fig. 4. (**a**) Outcrops of Bobonaro Scaly Clay near Venilale, in the study area; (**b**) Detail of scaly clay layer, green and reddish coloured.

according to Winkler's diagram (Fig. 6; Winkler, 1954), except for sample Ven1; in order to be used as a ceramic body for brick manufacture, this clay requires blending with a non-plastic material.

Mineralogically (Table 2), clay minerals clearly prevail over non-clay minerals, except for sample Ven1, which is characterized by a high amount of quartz (59%). Samples Ven2 and Ven3 are compositionally similar, except for smectite content (20 and 12%, respectively), with mineral assemblages comprising illite, kaolinite, quartz and smectite. Associated non-clay minerals include K-feldspar with smaller quantities of plagioclase, gypsum and hematite. The mineralogical composition is reflected in its chemical analysis. As would be expected, the lithotype Ven1 has the highest silica content (78.74%) and lowest alumina content (8.53%). The major oxide content of the two other lithotypes is very similar (Table 3). The red firing colour (900°C under an oxidizing atmosphere) is consistent with the Fe_2O_3 (5.07%) and TiO_2 (0.54%) content. Although these are preliminary data, due to the smectite content these clayey raw materials cannot be utilized with firing technology for the manufacturing of structural clay products (common and hollow bricks) and tiles for several reasons. In particular this is due to the occurrence of drying cracks, deformation during firing and small efflorescence. In order to overcome these drawbacks caused by the samples' high plasticity, the clays must be blended in the correct proportions with a non-plastic material.

The mineralogy of the sampled material does not confirm previous studies (ESCAP 2002), which refer to bentonitic clays in this particular area. Nevertheless, it is worth considering the occurrence of bentonitic clays in the area,

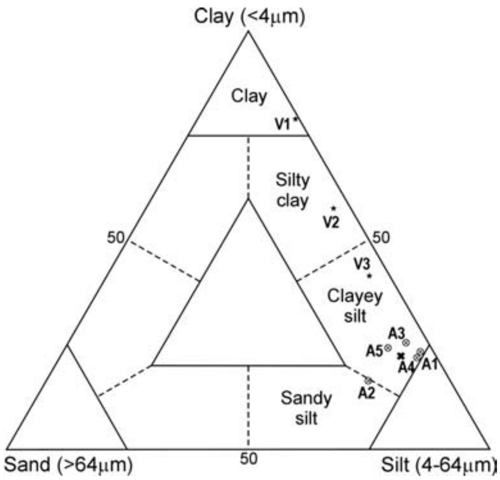

Fig. 5. Grain size classification diagram (Shepard, 1954): A1 to A5, Aileu samples; V1 to V3, Venilale samples; (×) average value.

which, although probably limited in distribution, should be assessed by sampling.

Aileu silt-rich deposits

The Aileu area, about 20 km south of Dili, is located in a valley, where thick coarse and reddish coloured river terraces crop out. Potential economic deposits of ceramic raw materials, characterized by light-coloured silt-rich sediments,

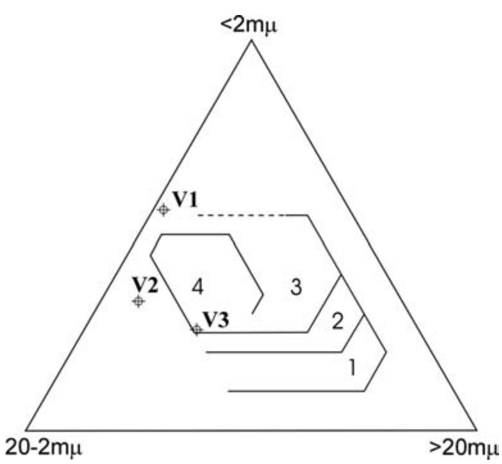

Fig. 6. Winkler diagram (Winkler 1954) for the technological classification of bodies for structural clay products: (1) Solid bricks; (2) vertically perforated bricks; (3) roofing tiles; (4) thin-walled hollow bricks. Venilale samples are V1 to V3.

which occur interbedded within the terraces, were studied. They do not represent a structural red ceramics target but its assessment was included due to its potentialities for whiteware ceramics under optimum accessibility conditions, which may trigger the development of a local industrial nucleus. The terraces and interbedded silt-rich deposits are confined by two faults striking WSW–ENE and other inferred fractures, which partially limit them, tectonically defining a graben, as shown in the mapped area presented in Figure 7.

Terrace composition is strongly related to the underlying bedrock, the Aileu Complex. In the study area it encompasses a series of light-coloured shales frequently interfingered with quartz veins. The targeted silt-rich deposits (maximum thickness of 25 m) occur in tabular layers, 0.5–3 m thick, encompassing silt, fine grain sand and clay (Fig. 8). Five channel samples representative of the deposit's predominant facies were collected for preliminary characterization studies. On the basis of their granulometry, studied materials may be classified as clayey silts, with the exception of sample Aileu2, which falls on the boundary between sandy silt and clayey silt fields of Shepard's diagram (Fig. 5; Shepard 1954).

Mineral assemblages of samples Ail1, Ail3 and Ail4 are quite similar, and samples Ail2 and Ail5 have the higher non-clay minerals content; illite is the prevailing clay mineral in all samples (Table 4). The high amounts of SiO_2 (64.89–72.85%), K_2O (3.39–4.18%) and fairly high Al_2O_3 (16.12–21.27%) reflect the quartz and illite contents of these samples; loss on ignition (LOI) values are concordant with the clay minerals' composition, mainly illite (Table 5).

Chemical analyses of the samples were plotted on a triangular diagram (Fabbri & Fiori 1985) to test the possible use of these raw materials as ceramic products. All samples fit into the white stoneware field, although relatively close to the edge, especially samples Ail3 and Ail2, the former with the highest total oxides content and the latter with the highest silica content (Fig. 9). The Atterberg limits obtained for whole samples show that apart from for sample Ail2, the remaining samples have a satisfactory to optimum extrudability and have a medium plasticity (Fig. 10). After firing (900°C under an oxidizing atmosphere), sampled clays behave in a way consistent with their mineralogical composition, forming a final product with a pearl-fired colour, homogeneous and without structural flaws.

The granulometrical, mineralogical and chemical studies as well as the clay's

Table 2. *XRD mineralogy of Venilale samples estimated by XRD analysis (wt%)*

Sample	Smectite	Illite	Kaolinite	Quartz	KF	NaF	Gypsum	Hematite	Calcite
Ven1	14	11	9	59	4	2	1	–	vest.
Ven2	20	28	24	21	4	1	1	2	vest.
Ven3	12	29	25	25	5	2	1	1	vest.

KF = K-feldspar, NaF = Na-feldspar.

Table 3. *Chemical analysis (wt%) of Venilale samples determined by XRF*

Sample	SiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	Na_2O	K_2O	TiO_2	LOI
Ven1	78.74	8.53	3.62	0.10	0.37	1.19	0.35	1.34	0.45	4.94
Ven2	60.65	16.51	5.73	0.25	1.79	1.87	1.16	2.87	0.58	8.29
Ven3	61.69	16.80	5.85	0.26	1.82	1.86	1.18	2.92	0.60	6.61

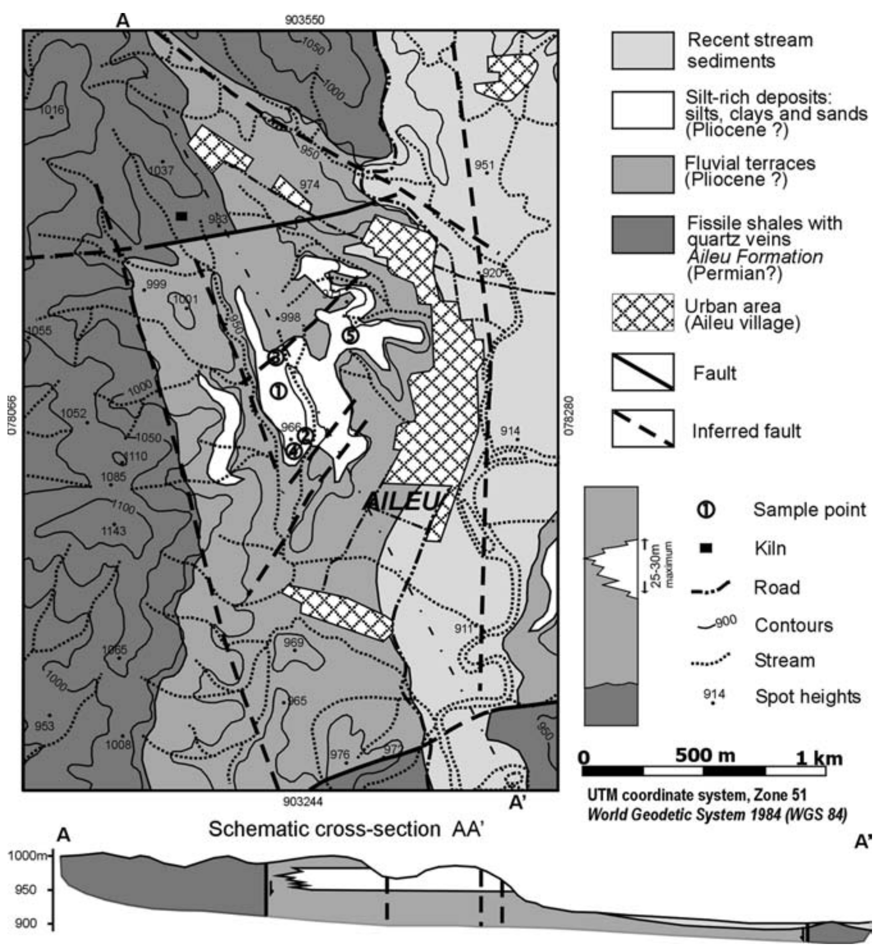

Fig. 7. Geological map of the Aileu area.

Fig. 8. Detail of the light coloured clay deposits.

workability, firing colour and final product characteristics, suggest that provisionally the raw material from the Aileu silt-rich deposits may be used for ceramic whiteware manufacture or for structural ceramic products if blended.

Other clay deposits in the Aileu area

Villages built on kaolin and a kaolin belt in Aileu region are mentioned in ESCAP (2002). In fact, the surrounding area of Aileu, especially towards the north of the city, contains large resources of *in situ* clay-rich deposits, resulting from the alteration of shale or alluvium deposits. Although vast quantities of clay-rich material occur, the *in situ* deposits are characterized by embedded quartz fragments, resulting from a complex interfingering of quartz veins frequently found in the Aileu Formation's shales. Moreover, the occurrences are scattered and too small for the development of an industry with modern firing technology. Clays in alluvium deposits have unfavourable exploitation conditions, due to their topographic locations near stream channels, exposing them to the risk of seasonal flooding. Nevertheless, they are exploited by

Table 4. *Mineralogy of Aileu samples estimated by XRD analysis (wt%)*

Sample	Ill/Verm	Illite	Kaolinite	Quartz	K-Feldspar
Ail1	2	47	24	26	1
Ail2	1	32	14	51	2
Ail3	4	50	21	24	1
Ail4	2	38	20	38	2
Ail5	1	31	16	50	2

Ill/Verm = mixed-layer illite/vermiculite.

Table 5. *Chemical analysis (wt%) of Aileu samples determined by XRF*

Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	LOI
Ail1	67.51	19.41	1.90	0.79	3.72	<0.2	0.84	5.63
Ail2	72.85	16.12	1.60	0.69	3.43	<0.2	0.79	4.42
Ail3	64.89	21.27	1.72	0.95	4.18	<0.2	0.85	5.93
Ail4	68.78	18.73	1.40	0.80	3.62	<0.2	0.87	5.43
Ail5	71.67	16.90	1.47	0.76	3.39	<0.2	0.83	4.98

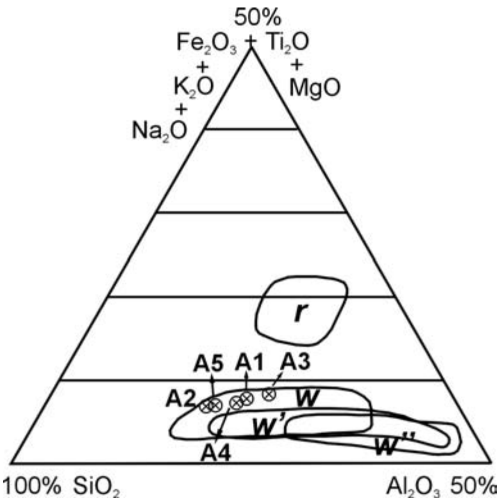

Fig. 9. Chemical composition of studied raw materials in comparison with red stoneware (r) and white stoneware (w = German; w′ = English; w″ = French) application fields; Aileu samples are A1 to A5.

local people for the artisanal making of sun-dried bricks. It can be concluded that the Aileu region is an important source of clay raw materials and warrants further investigation. Although the expected deposits are small and widely scattered, they may in time support an industry based on the blending of different types of clay to ensure adequate quality and sufficient reserves.

Ornamental stones

Ornamental stone exploitation has long been important in countries such as Italy, Spain and Portugal and, more recently, in developing countries such as Brazil, India and China. In general, ornamental stones are relatively high-value products. The establishment of an ornamental stone mining industry in Timor Leste could play an important role in its economic and social development. However, it is important that large-scale environmental impacts are avoided and mitigated against, in particular degradation of the landscape, as this may impact on the development of a tourist industry.

Favourable criteria for ornamental stone resources include high lithological thickness, lithological uniformity, and moderate fracturing grade. In Timor Leste, there are several geological units, such as the Aileu, Maubisse, Borolalo Limestone and Cablac Limestone formations (Table 1) that meet (at least partially) those broad criteria and thus are potentially suitable for the ornamental stone extractive industry. The Beuah marbles (Aileu Formation) and the Beheda limestones (Maubisse Formation) were selected for follow-up investigations.

Beuah marbles

Owing to the existence of an old marble quarry near Beuah village in Manatuto district, east of Dili, during the last years of Indonesian

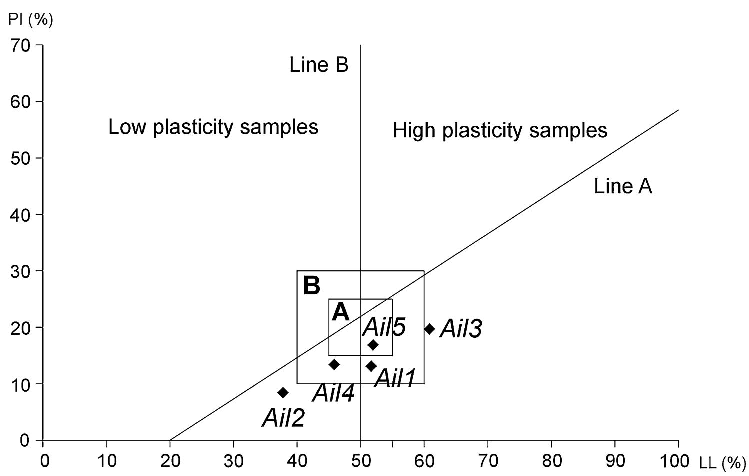

Fig. 10. Casagrande diagram with domains (Gippini 1969) relative to extrudability of ceramic raw materials: A, optimum; B, satisfactory; empirical boundary ‘Line A’ separates inorganic clays (above the line) from inorganic silts and organic soils; ‘Line B’ separates raw materials with low plasticity from those with high plasticity; PI, Atterberg plasticity index; LL, Liquid limit.

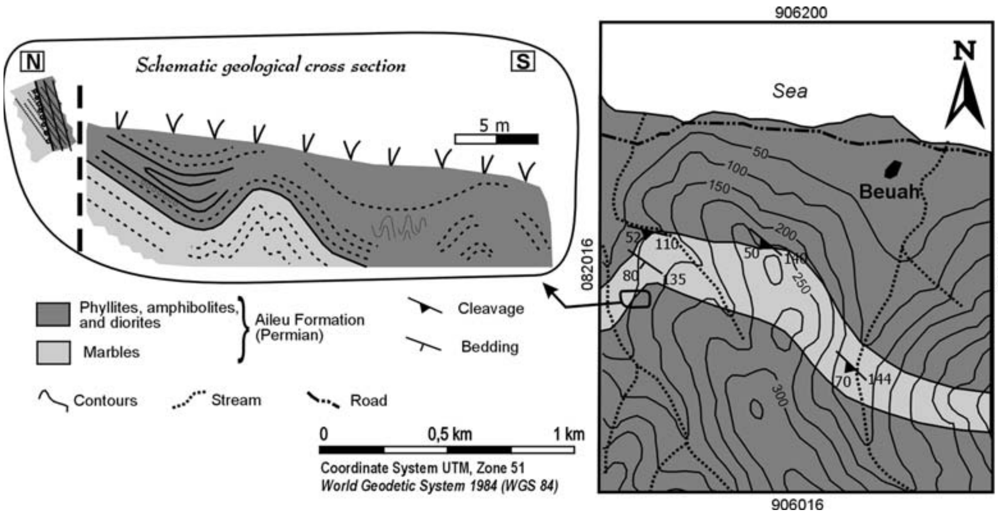

Fig. 11. Geological map of Beuah area.

occupation, marbles are referred to as one of the potential economically exploitable mineral resources of Timor Leste (ESCAP 2002; WFB 2004). They represent a minor lithological component of the northeastern multiply-deformed Aileu Metamorphic Complex sequence, occurring in layers usually less than 100 m thick (Berry & Grady 1981).

Fig. 12. Structural aspects of Beuah marbles. Two phases of deformation can be recognized in the folded structure.

A preliminary geological study of the area where exploitation took place (Fig. 11) shows that marbles crop out along a belt about 200 m wide, which corresponds to a deposit with an apparent thickness of approximately 50 m. However, the real deposit thickness is difficult to estimate due to the polyphase deformation: at least two phases of folding can be recognized (Fig. 12). Marble outcrops in the study area seem to represent the inverted flank of a north-verging major fold, although insufficient data did not allow a conclusive characterization of the structure.

The marbles cropping out in the study area show significant texture and colour variations. The exploited lithotypes are typically light coloured (white, pale pink or yellow) and fine grained with few grey streaks of dark schistose material (Fig. 13). However, such lithotypes occur mainly within the central area. Laterally, there is a variation to a greyish dark coloured facies with numerous streaks of dark schistose material crisscrossing the marble, which is fine to coarse grained. The presence of interbedded fine layers (about 1 to 3 cm thick) of calcsilicate rocks (Fig. 14), as well as coarse, weathered, red garnets reduce the quality of the marble.

Marble quarrying in the area was based on the exploitation of large boulders from a colluvium deposit. Their provenance is a steep area to the south, where the marbles crop out at 300 m in

Fig. 13. Remaining marble blocks from Indonesian exploitation and detail of the most commonly used lithotype.

elevation. Owing to their inaccessibility, the extractive activity never focused on these *in situ* outcrops. Attempts were made to exploit the deposits situated in the valleys east and west of the above mentioned central area, but the exploitation was abandoned as a consequence of the lateral variations to dark coloured facies and structural complexity. All things considered, it is likely that these deposits may prove unfavourable for exploitation. Nevertheless, as evidenced by Berry and Grady (1981), there are much larger marble occurrences to the south of this area that warrant assessment.

Fig. 14. Greyish marble outcrop with thin calcsilicate layers.

Beheda limestones

In the surrounding area of Beheda village (10 km west of Manatuto), widespread outcrops of the Maubisse Formation reveal the economical potential for ornamental stone extraction. Moreover, proximity to the main road between Dili and Baucau and good accessibility conditions, makes this area very attractive for the extractive industry.

The unmetamorphosed Permian Maubisse Formation is a sequence of carbonate-rich and volcanic rocks, where fauna-rich massive limestones prevail at the base of the unit (Audley-Charles 1968). Its geological origin and settlement has been the object of controversy, including its association with the Aileu Formation (Barber & Audley-Charles 1976; Carter *et al.* 1976; Barber *et al.* 1977; Charlton *et al.* 2002). In the Beheda area, the Maubisse Formation is represented by crinoid-rich limestones that crop out as a *klippe* overlying parautochthonous Mesozoic terrains of the Wai Luli Formation, which mainly consists of shales, marls and sandstones (Fig. 15).

The mapped Maubisse Formation's limestones occur in an elongated area oriented NE–SW, 500 m in width and 1500 m in length. The outcrops are large, occurring in blocks as shown in Figure 16, the largest of which are approximately 50 m^3 with very few fractures. Owing to the

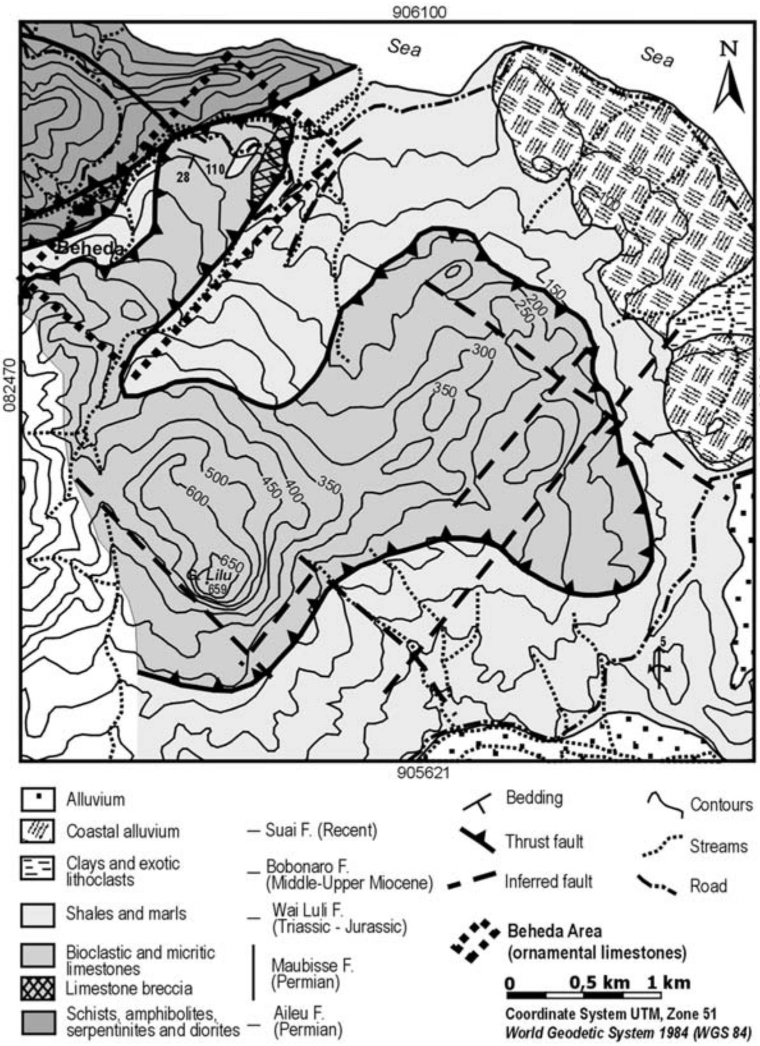

Fig. 15. Geological map of Beheda area.

massive structure of the limestone, it becomes difficult to estimate its thickness, which is probably between 3 and 6 m. Beds dip gently from 10 to 25° SSW. Two main facies coexist:

- A prevailing facies of white to very light coloured biocalciclastic limestones (biocalcarenites), medium to coarse grained with sparry cement. White coloured crinoids are the most abundant bioclastic elements. Their average size is approximately 1 cm, but they reach up to 5 cm (Fig. 17).
- Micritic (calcilutites) to microsparritic limestones, light to dark grey in colour, with disseminated fine bioclasts and calciclasts. Large bioclasts can also occur, as well as abundant translucide calcite veins (<2 mm thick). The biocalciclastic limestones abruptly and conformably overlay this facies.

Both facies are potentially suitable for use as ornamental stone, in particular the crinoid-rich limestones. Evaluation of the resources in the study area considered geological structure and the raw material's final use. Considering the inherent restrictions to the yield of a typical ornamental stone exploitation, a probable resource of 300 000 m^3 is inferred by simple geometric

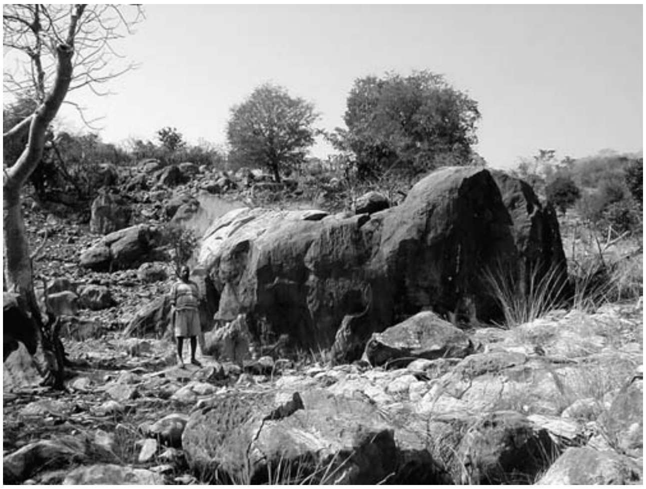

Fig. 16. Huge limestone outcrop in Beheda area.

calculations. Although this value does not support long-term modern industrial exploitation, the country's economic and social situation is rather favourable for small-scale operations, since they do not require sophisticated machinery. These limestones can also be used as raw materials for lime or cement production. In these circumstances the available resources are much larger. In a sustainable approach, aggregates should always be considered as a subproduct of any ornamental stone exploitation.

The area warrants further detailed investigation and future work should also consider a thematic geological mapping approach for the Maubisse Formation's extensive outcrops, south of the study area. These could provide large volumes of raw material suitable for the production of lime, cement, crushed-stone aggregates or, possibly, ornamental stone.

Aggregates

Aggregates are used as construction raw materials, with or without a binder. Road base or road surfacing material and macadam are the major envisaged uses without a binder in Timor Leste. Aggregates for cement and bituminous concrete in road construction and repair, and in

Fig. 17. Detail of crinoid-rich limestone from Maubisse Formation in Beheda area.

residential and public building construction are the major likely uses with a binder. Other important uses include cement and lime manufacture and soil correctives in agriculture. Despite their low bulk value, aggregates are among the most important commodities, being major contributors to the economic and social well-being of nations and are key to sustainable development (Wellmer & Becker-Platen 2002; Cárdenas & Chaparro 2004; Langer & Tucker 2004).

Aggregates are a very important commodity in Timor Leste, playing an increasingly important role in the immediate future development of the country. Extensive rock deposits, with the potential for aggregate resources, are found all over the island. Sources for crushed stone encompass rocks of diverse lithostratigraphical units. The most important ones are the Aileu Complex (igneous and metamorphic rocks), the Cablac Limestone and the Maubisse Formation (limestones and dolostones). The main source of superficial sand and gravel aggregates in Timor Leste is stream channel deposits within the Suai Formation.

Crushed stone

Intermediate to ultrabasic intrusive hard rocks are relatively common in the northern part of the Aileu Complex. They are an excellent source of crushed stone aggregates, which could be an important resource of high-quality raw material suitable for road metal (road-base aggregates), as well as for armour stone for harbour and pipeline protection.

In Dili's coastal region, and to the west of the town, extensive outcrops of these rocks are common with good accessibility. Examples of such areas include Cristo Rei and Comoro River (in the surroundings of Dili) and Maubara and Tibar-Liquiça (some kilometers to the west of Dili). In the latter area an important but now inactive quarry once exploited a competent dark-green igneous basic rock that crops out for more than 400 m along the coastal road. Although strongly fractured, these fine to medium grained rocks are not significantly weathered, making them suitable for crushed stone production. Resources are extensive, but an assessment of the material's physical and chemical properties has yet to be undertaken. The area is important due to its proximity to the country's capital, the major consumer and trade centre.

In terms of accessibility and proximity to other main villages, the most relevant limestone and dolostone occurrences are the Maubisse Formation outcrops in Maubisse district and the Cablac Limestone Formation outcrops in Viqueque district. As mentioned elsewhere, the Maubisse Formation lower sequence is characterized by prevailing massive limestones, which have a high potential for ornamental purposes, as is the case for the outcrops near Beheda village. Thus, aggregate production from Maubisse Formation limestones must be regarded always as a byproduct of the eventual exploitation for ornamental stone, contributing to a prudent use of this natural resource.

The Cablac Limestone Formation has been dated as Lower Miocene (Audley-Charles 1968) and is mostly composed of thick bedded, hard, massive limestones that commonly occur in mountain tops as steep outcrops (e.g. Baucau, Viqueque and Covalima districts). Although the general study carried out on these limestones suggested a high economic potential for ornamental purposes, they are also suitable for crushed stone aggregates. These rocks have high potential for using as concrete aggregate, as they are hard and clean. In addition, their use in cement and lime industries should not be disregarded. In the Ossu village area (Viqueque district), a conglomeratic facies of this formation is exploited in a small quarry about 2.5 km north of Ossu, for road building purposes (Fig. 18).

Other predominantly carbonate-rich units, but with more restricted uses are the Baucau Limestone and the Viqueque Formation. The Baucau Limestone Formation (Baucau and Lautem districts) is referred to as a fossilized coral reef and associated carbonate-rich deposits dated as Pleistocene to Holocene in age (Audley-Charles 1968). These are exploited in small artisanal works and crushed to obtain a sand grain size aggregate, which is used locally as filler in the production of cement made bricks. The purity of these limestones makes them an optimal raw material for lime production. The facies composed of carbonate-rich rocks in the Viqueque Formation (mainly in the Viqueque district), dated as Upper Miocene to Pliocene (Audley-Charles 1968) is used for the same purpose. These rocks, particularly a white marl distinctive facies that crops out extensively in the Viqueque's surrounding area, might possibly have another potential use as a cement raw material. Nevertheless a detailed assessment of their chemical and physical properties needs to be undertaken.

Sand and gravel

Owing to the climatic, topographic and tectonic conditions of the Timor island, alluvium deposits are thick and vast. The torrential weather regime produces wide stream channels with thick

Fig. 18. Small quarry in Ossu area, where a conglomeratic facies of Cablac Limestone Formation is exploited.

unconsolidated deposits of mostly unsorted material, even in upstream areas. Their nature is very diverse depending on the source lithologies.

The most important river courses in the north coast occur within the Aileu Complex. The deposits are characterized by the presence of clasts, ranging in size from pebbles to metric boulders of schistose rocks, gabbros and quartz within a clay matrix. In the east of the country, where argillaceous and carbonate-rich rocks of Triassic to recent aged formations predominate (Fig. 2 and Table 1), sand and gravel deposits are not as thick, and are mostly associated with talus deposits and storm waves accumulations of coral reef rocks in beaches. The main sand and gravel exploitations are located near the coast road between Liquiça and Manatuto. The large valley of the Comoro River, located in the Dili area, is the main aggregate source (Fig. 19). The alluvium deposit is a poorly sorted material composed of greyish schistose and quartz clasts of sand and gravel, with larger clasts, mainly of igneous mafic rocks. The material is embedded in a silt and clay matrix. The presence of elongate and/or flaky particle shape of foliated

Fig. 19. Sand and gravel exploitation in Comoro River, Dili. Note the numerous small pits dug by local miners.

rock and of mafic minerals, iron oxides and clay reduces the quality of this raw material. It is, however, exploited by a large number of artisanal miners, who sort out sediments of different size grades by hand screen. Despite the poor aggregate quality of this material for use in the building industry, its consumption is primarily as sand for concrete and cement bricks. Gravel is used in road building and repair.

The sand and gravel resources of Timor Leste are extensive. In addition to the Comoro River, other river valleys have large and thick alluvium deposits, such as the Laclo Norte River near Manatuto, the Laleia River between Laleia and Vemasse, the Lois River between Balibó and Maliana, and the Cua River near Viqueque. The artisanal procedure for exploiting these deposits is not expected to cause relevant modifications to the streamline dynamics. However, considering the country's expected development and the consequent technological enhancements in industry, the exploitation process should be reformulated in order to avoid pervasive environmental disturbances.

Discussion and conclusions

Timor Leste is the poorest country of the Asia–Pacific region due to the devastating and violent incidents that occurred in 1999. To promote the economic development of the country, a strategy of infrastructure reconstruction has been outlined, for effective impact on poverty reduction. However, it is impossible to plan for major infrastructures such as roads and bridges or houses and public buildings without considering the mineral resources and raw materials required to construct them.

This work has focused on the identification of mineral resources suitable for use as construction raw materials, namely aggregates, common clays and building stones. In Timor Leste, these resources are crucial, both directly and indirectly for infrastructure reconstruction, maintenance and future developments, thus contributing to and determining its sustainable development.

In order to support an emergent extractive industry, a few target areas were identified, although many favourable areas for construction raw material certainly exist. In Venilale, a village with good access to Baucau, the second largest city in Timor Leste, large resources of common clays occur over a large area. Although the results of preliminary sampling and characterization were not favourable due to the materials' high plasticity, these clayey materials could support brick- and tile-making industries, if properly blended with a non-plastic raw material. A regional sampling programme could be successful in identifying areas with more adequate ceramic properties, although the formation has a characteristically high smectite content (Audley-Charles 1965, 1968; Harris *et al.* 1998).

The ceramic industry is perhaps the industry that could most easily be developed due to the traditional skills that still remain as a result of the old ceramic plants in Dili. Besides providing raw materials for the building industry, it could provide employment opportunities, training of skilled human resources, and encouragement of an internal trade economy, thus contributing to the overall economic development of the country. In the longer term, bricks and roof tiles could be exported to neighbouring countries, particularly to Indonesia.

In the surrounding area of Manatuto, located half way between Dili and Baucau, large and massive limestone outcrops may be used in the ornamental stone industry. They may represent an important commodity for Timor Leste not only for internal consumption, but also for exporting purposes if extensive deposits are to be found. Although the immediate requirement of Timor Leste is not the embellishment of its buildings, ornamental stones are an important commodity as they can perform a structural role in the building industry, replacing other materials that otherwise must be imported. With regard to eventual exportation of this commodity, the benefits for the economy are obvious. Nevertheless, this option must be supported by an adequate market study, particularly focusing on potential markets in neighbouring countries.

A major issue that must be addressed regarding the establishment of an ornamental stone's mining industry in Timor Leste is the lack of technical means and human skill resources required to exploit, saw and polish large blocks of stone. Intervention by foreign companies will be crucial for the development of this industry and for training local counterparts. This area is also the stepping-stone to areas where the Maubisse Formation crops out (east of Luro, Tapau and Balibo areas and south of Vemasse), which can be considered potential targets for ornamental stone exploration.

Environmentally, the extraction of ornamental stones is one of the most problematic in relation to landscape degradation. This is due to the often common, large accumulations of residues or waste. To ensure the prudent use of this resource, the byproducts of ornamental stone production should, as far as economically possible, be used for other purposes such as crushed stone aggregates.

The importance of aggregate resources across the world has long been recognized, to support both developing and developed economies. Timor Leste has extremely large aggregate resources, in particular river sand and gravel deposits. Other important aggregate resources include crushed stone aggregates from hard, basic intrusive rocks near Dili, the main consumer centre. Nevertheless, owing to the country's geological diversity, almost all major consumer centres are within close proximity to hard rock resources suitable for crushed stone aggregates and/or in the vicinity of sand and gravel alluvium-rich stream channels. Irrespective of the resources type, the key concern is ensuring that these resources are exploited in a sustainable manner, economically, environmentally and to the maximum social benefit.

Even in developed countries, geological information and interpretation has been used to a limited extent in exploration and exploitation of construction raw materials as a result of the resources' near surface relationship and worldwide abundance. This has indirectly and negatively affected the integration of the extractive industry into land use planning in many developed countries, particularly in Europe. The concerns of accessing mineral resources by the extractive industry can be avoided if adequate land use planning methodologies are adopted in Timor Leste regarding not only agriculture and tourism as sustainable development factors, but also mining.

The emergence of a large number of unsustainable small artisanal mining activities in Timor Leste, proximal to the larger consumer centres, is a response to the country's infrastructure reconstruction raw material needs. Most of them are exploiting sand and gravel in large stream channels without any environmental considerations or work security issues. Although aggregates, common clays and ornamental stone are essential raw materials for the reconstruction of the country's infrastructure, their commonly adopted exploitation methodologies can, if not planned and managed in a sustainable manner, result in large visual impacts on the landscape and, consequently, a negative opinion of the mining industry.

A short-term policy adapted to the country's raw material requirements and to the current lack of human skill resources and technological processing capabilities is a major challenge that must be addressed in order to create mining investment opportunities within a framework of sustainable development. Perhaps one of the ways forward is to support present-day artisanal mining activity through the promotion, development and regulation of small-scale mining industries. In the short to medium term, this would satisfy market demands, contribute to unemployment reduction (as it could be carefully planned to employ large numbers of Timorese personnel) and reduce the country's dependency on imported goods.

These small-scale industries should not be confused with the small-scale artisanal mines that are typified worldwide by an absence or low degree of mechanization, precarious safety standards, poorly skilled and paid personnel, and illegality due to the inexistence of mining rights. Instead, the well-known issues associated with these environmentally and socially problematic mines should be considered as business practices to avoid. The Berlin II Guidelines for Mining and Sustainable Development (UNEP 2002) is a starting point for the implementation and control of a sustainable development indicator system for the extractive industry. However, care must be taken that such a system should take into account the amendment and customization of indicators to the specificities of Timor Leste.

In this context, Timor Leste's government can play an important role in ensuring mineral resources are acknowledged as a key determinant of the country's sustainable development, but also key to the promotion of sustainable development principles in the mining industry. Institutional capacity in the fields of Earth Sciences and mineral resources management is the key to the discovery and promotion of new deposits, to the integration of the mining industry into land use planning policies and to the promotion of extractive activities with minimal environmental impact.

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