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Anthropogenic geomorphic change as a potential generator of renewable geologic resources in the humid Pampa of Argentina

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ABSTRACT

The nature and amount of sediments in various lakes, intermittent swampy areas and river sectors in the humid Pampa (Buenos Aires Province, Argentina) were analysed. The aim was to determine whether recent sediments in such environments could serve as an alternative resource to the brick industry, for minimising the current, high environmental impact of soil mining. Sediment sequences were obtained, and the thicknesses of the upper sediment layers, corresponding to the suballuvial (approx. 1400–700 years BP) and alluvial (approx. 250 years BP to present) were determined. Sediment samples were collected and analysed for grain size and Atterberg limits. Suitable sediments were then selected to determine the optimal brick materials and their technical properties. Similarly, control bricks were prepared with ceramic pastes of local industries. The results show that the quality of the former is similar or superior to that of the latter. The initial estimates of the available resource indicate a long-term supply for the industry. Estimates of the current sedimentation rates indicate that resource renewal might occur at a rate comparable to current consumption. The sedimentation rates have increased significantly in the past two centuries – more so in the past few decades (the Anthropocene?) – with increasing human modification of geomorphic processes. If the results presented here are confirmed, a highly sustainable model can be implemented in the brick industry.

1. Introduction

A ‘geomorphic dimension of global change’ or a ‘global geomorphic change’ may be in place, as noted by researchers (Cendrero and Douglas, 1996; Rivas et al., 2006). These terms refer to changes in the rates of geomorphic processes due to human modifications of the land surface and not climate change. These changes are occurring at a global scale, typical of the Anthropocene, which affect the rates of geomorphic processes, and the frequency of related natural hazards (Cendrero et al., 2006; Bonachea et al., 2010; Forte, 2011; Bruschi et al., 2012a,b, 2013). Such geomorphic changes lead to direct, deliberate excavation and transport of rocks, sediments and soils and indirect, unintended erosion due to human activities that disturb the land surface. In general, human-induced geomorphic changes have led to increasing surface geologic processes, particularly after the middle of the 20th century, coinciding with the sharp increase in human activities and their effects known as the ‘Great Acceleration’ (Steffen et al., 2004, 2011, 2015). The Great Acceleration represents a ‘great geomorphic acceleration’ (Bruschi et al., 2013; Bruschi et al., 2012a,b; Hurtado et al., 2012), which can be problematic but beneficial as well.

The humid Pampas, in Argentina, is an interesting case study. This region is characterised by a significant ‘human geomorphic footprint’ (Rivas et al., 2006) due to soil mining for brick making. The Pampa is a loess-dominated plain with limited materials that are suitable for construction. Thus, brick construction has flourished here, with soil being used as a raw material. Since the 19th century, soil mining has been the main source of raw materials for brick making in the humid Pampa and other areas of Argentina (Del Río et al., 2001; Forte et al., 2004; Hurtado et al., 2008). At present, this activity is primarily responsible for the relief modification and sediment transport seen in the area, as well as the significant environmental degradation, particularly around urban centres (Giménez et al., 2002; Rivas et al., 2006; Hurtado, 2015). Similar effects of soil mining have been described across various parts of the world (Lal, 1997; Yadav, 2003; Singh and Asgher, 2005; Haack and Khatiwada, 2007; Zhang and Fang, 2007; Gupta and Narayan, 2010; Santhosh et al., 2013).

Increased sediment generation is highly prevalent worldwide (Judson, 1983; Kesel et al., 1992; Walling, 2000, 2006; Yang et al., 2004; Syvitski et al., 2005; Knox, 2006; Syvitski and Milliman, 2007; Wilkinson and McElroy, 2007; Syvitski and Kettner, 2011; Milliman

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and Farnsworth, 2011). Increasing sediment production and silting of lakes and ponds due to soil erosion in farmlands and sites affected by human-induced excavation/accumulation processes have been reported for various study areas (Hooke, 1994; Douglas, 1996; Ziegler et al., 2000; Phippen and Wohl, 2003; Gellis et al., 2004; Ramos-Scharrón and Mac Donald, 2005; Chin, 2006; Rivas et al., 2006; Carvalho et al., 2010). In the study region, several shallow lakes have been converted to 'bañados' (swampy areas covered with water for a short period annually) via sediment deposition. Thus, areas used for recreation and fishing are lost, and their natural flood-buffering capacity is reduced (Dangavs et al., 2006; Dangavs, 2008; Dangavs and Reynaldi, 2008; Dangavs, 2010). Thus, most of the sediment carried into the lakes originates from the erosion of the topsoil, the A and, to a lesser extent, B horizons, those used for brick making.

The aim of the present study was to assess alternative resources for brick making to minimise the environmental impacts related to soil mining. Thus, with suitable alternatives, two environmental degradation problems related to geomorphic change – land degradation caused by soil mining and floods – can be mitigated. Further, the soil mining activity in the region can be significantly reduced or eliminated altogether. The natural – although human-enhanced – erosion process can provide raw materials for the building industry sustainably, and the extraction of lake sediments can help maintain the depth and flood-buffering capacity of lakes.

In the ceramic industry, soil mining has been performed for a long time and remains a common practice in other parts of the world (Mbumbia et al., 2000; Singh and Asgher, 2005; Zhang and Fang, 2007; Ngon Ngon et al., 2009; Nzeukou et al., 2013; Santhosh et al., 2013). The possibility of using sediments as raw materials for brick making has also been explored (Bhatnagarjm et al., 1994; Chiang et al., 2008; Samara et al., 2009; Mezencevova et al., 2012; Cappuyns et al., 2015). Various other raw materials may be explored with similar approaches to obtain results comparable to that of the present study.

2. Study area

2.1. Main environmental characteristics

The area selected for the study is a sector of the humid Pampa in the Buenos Aires Province, southeast (SE) of the Buenos Aires conurbation (Fig. 1). The region has a 250–1500-m-thick Miocene–Quaternary sedimentary cover, over a Paleozoic–Precambrian basement. The upper layer is composed of loess sediments of the Buenos Aires and Ensenada formations – the 'Pampeano', deposited between 700,000 and 10,000 years BP (Iriondo, 2010) – covered by aeolian and fluvial post-Pampean sediments (Fig. 1). The surface of these formations has been subject to successive erosion and deposition processes with the alternating dry and wet periods beginning approximately 10,000 years ago. Before the Little Ice Age (LIA), a wet period occurred around 1400–700 years BP. The lake sediments discussed in this study began to form during this period (Iriondo and García, 1993; Iriondo, 1999) and they continue to be deposited.

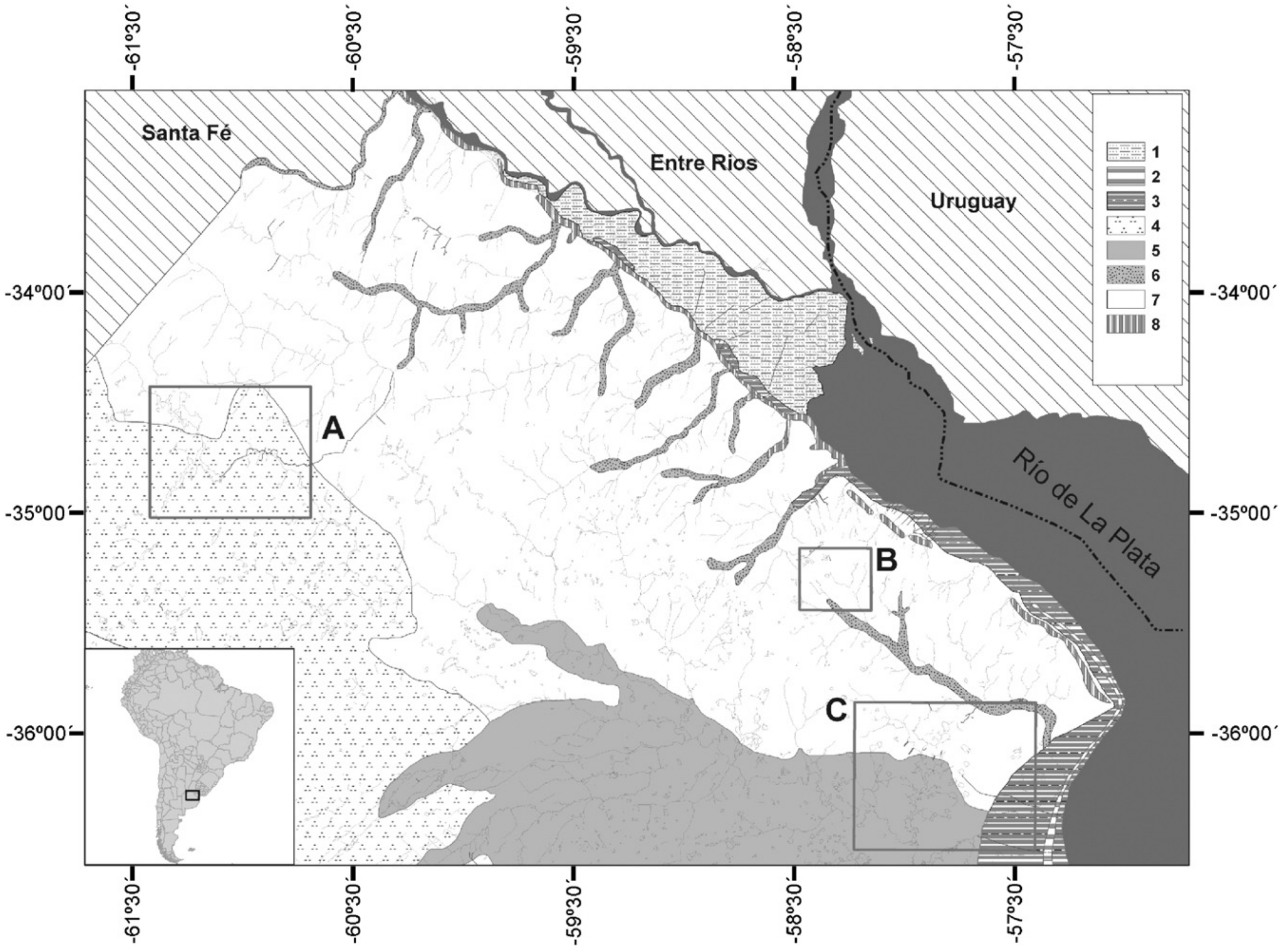

Fig. 1. Location map and simplified geologic map of the study area. Areas within frames are shown with more detail in Fig. 6. 1: Delta deposits. 2: Querandí Formation (marine, shell deposits). 3: Querandí Formation (marine-estuarine, organic clay-silt deposits). 4: Junín Formation (continental, eolian sand deposits). 5: Lacustrine clay and silt deposits. 6: Luján formation (fluvial, silt-clay deposits). 7: Buenos Aires Formation (continental, silt-clay loess deposits. 8: Ensenada Formation (continental/marine, loess silt/sand-clay). The coastal plain coincides essentially with the area occupied by the Querandí Formation.

Two main environments can be identified (Frenguelli, 1950, Fidalgo and Martínez, 1983; Fidalgo et al., 1991; Cavallotto, 2002): (A) the coastal plain, a flat, swampy area, generally below an altitude of 5 m, with marine and fluvio-estuarine deposits formed during late Pleistocene–Holocene transgressions and regressions, which alternate; and (B) the continental area, in which the upper formations are of fluvial and loess origin. The relief is extremely gentle, with maximum altitudes <50 m and very low gradients, often <0.5% and rarely >2.0%. Therefore, water frequently accumulates in several flat, poorly drained areas or blowout depressions present across this area (Fig. A; supplementary information). The lakes and deposits studied here are located in the continental area, as are the majority of soil mining operations. Soils in this unit are mainly typic and vertic argiudols, thapto-argic hapludols and typic hapluderts.

The humid Pampa contains several thousand lakes and wetlands of varying types and sizes (Fig. A; supplementary information). They represent a valuable environmental resource, for example, for sports and commercial fishing, reed harvesting, hunting, recreation and tourism and regulation of the water cycle during flooding. According to Dangavs (2005), the Buenos Aires Province has some 146,000 lakes over areas of 0.01–10 ha, and approximately 10,500 lakes spanning >10 ha. The same author reported a total area of lakes within the province of 3175 km^2. No detailed data on the number of 'bañados' and the area covered are available, although the unsystematic survey performed for this study revealed several of these. They are likely to cover a total area similar to lakes. Lakes and 'bañados' are likely to cover 4000–5000 km^2, which is a very conservative estimate.

The climate is temperate humid, with annual rainfall ranging between 900 and 1200 mm. The land cover and land use primarily comprise pasturelands and farmlands. The main crops include soy and various cereals. Horticulture and floriculture are key activities in certain areas surrounding cities. Urban land is also of importance, as the Buenos Aires conurbation comprises a population of approximately13 million. Areas with more or less natural vegetation represent a very small proportion, which are essentially limited to a part of the margins along the Rio de la Plata estuary.

2.2. Sedimentary sequence in lakes

The typical sedimentary sequence of these lakes (Fig. 2) overlies the Buenos Aires and Ensenada formations (sandy silts; middle and upper Pleistocene, respectively). The first lake deposit is represented by Upper Pleistocene fluviolacustrine brown–grey sandy silts (Luján formation, La Chumbiada member; 3, in Fig. 2; Dillon and Rabassa, 1985), dating as far back as >28,000 years BP. The next level is composed of greenish clay pellets flocculated around fine sand grains (La Postrera I formation (4); Dangavs, 1979). It is considered to be formed via aeolian processes during a dry and cold period from 28,000 to 18,000 years BP. The top layer comprises green–yellow sandy silts and clays with epigenetic gypsum (Luján formation, Lobos member (5); Dangavs and Blasi, 2003). They were formed in brackish and freshwater environments, during a wetter and warmer period, between approximately 18,000 and 8500 years BP. In some locations, a new aeolian deposit, La Postrera II (6), overlies this layer. The next layer is composed of light-grey clayey sediments with abundant fossil remains of freshwater organisms and volcanic ash. This is the Rio Salado member of the Luján formation (Fidalgo et al., 1973), equivalent to the Platense of Ameghino (1884), attributed to a warm and wet period from 8500 to 3500 years BP.

Grey sandy clay and silt deposits appear over the former unit, but only in some lakes. These deposits correspond to the suballuvial (Doering, 1884) or Aimarense (Ameghino, 1889), attributed to a new wet and warm period, spanning 1400–700 years BP. In some cases, a brown–grey loess deposit is observed, which is affected by soil-forming processes and is sometimes mixed with the above layer, attributed to the cold and dry period of the LIA, and the La Postrera IV formation (10; Dangavs, 2005). Finally, above this layer appear the sediments accumulated after European occupation of the territory. They are assigned to the alluvial formation (11; Valentín, 1898). Various authors attribute the beginning of this period to 300–150 years BP (Villalba, 1994; Villalba, 1990; Thompson et al., 2003; Bertranda et al., 2005; Araneda et al., 2007; Meyer and Wagner, 2009).

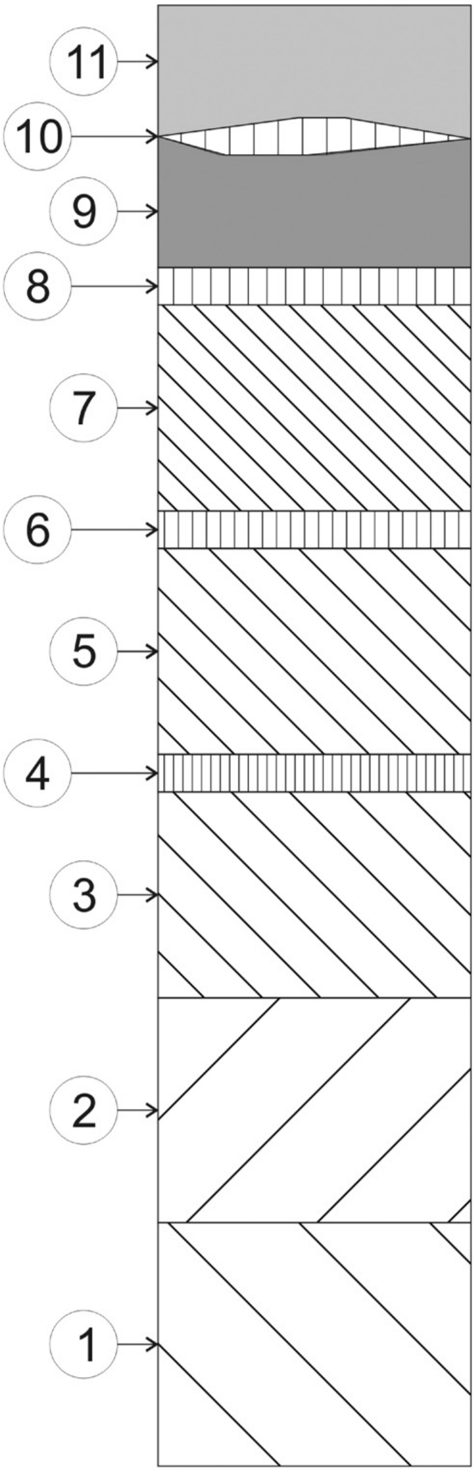

Fig. 2. Idealised sedimentary column for the study area (see description in text). Thickness of the different units not to scale, because they differ between lakes. Some units, especially eolian deposits, are not always present. This is illustrated only for La Postrera IV. 1. Ensenada Formation, 2. Buenos Aires Formation, 3. Luján Formation, Member La Chumbiada, 4. La Postrera I, 5. F. Luján, M. Lobos, 6. La Postrera II, 7. F. Luján, M. Río Salado, 8. La Postrera III, 9. Suballuvial, 10. La Postrera IV, 11. Alluvial.

At present, the deposited sediments originate from two main sources: fine dust brought by wind from distant sources on the one hand, and clay, silt and organic matter generated within the lake's basin via erosion of the A horizon on the other. Erosion of lake margins by waves leads to the formation of some carbonate gravels, derived from older sediments. The sediment accumulation leads to a gradual reduction in lake depth and rooting of vegetation, such that the lake is eventually filled and transformed into an intermittent swampy area or 'bañado'. Most lakes have two different environments. Sand and silt are predominant near the margins, where sediments are transported primarily as bed load and fine gravel. Suspended load is predominant in the central regions, with the sediment being formed by silt and clay and, in some cases, fine sand. Naturally, the grain size tends to decrease towards the innermost regions.

2.3. The brick industry in the humid Pampa and its environmental effects

Soil is used as a raw material by brick manufacturing industries in the area. The topsoil (A horizon) is exploited for manufacturing traditional, solid bricks, whereas the B (mainly Bt) horizon is the major material for producing hollow bricks (Fig. 3). The argiudols are primarily extracted, as well as hapludols and hapluderts, which offer not only the best-quality material but also the highest soil capability and productivity (INTA, 1990; Giménez et al., 1992; Hurtado et al., 2006, 2004; Hurtado, 2015). Most exploitations are limited to the decapitation of the A horizon, but some of them also involve horizon B. Approximately 0.2–0.3 m of the former is excavated and usually not more than 1.5 m in the latter. In some cases, the deeper layers are exploited for various purposes (sub-base for roads and buildings, etc.). These layers can be excavated up to a depth of 15–20 m (Fig. 4).

The case of La Plata (approximately 650,000 inhabitants; Fig. 5) is representative of the industry in the area. The brick consumption from 1882 (when the city was founded) to 2001 is estimated to be approximately 250 bricks person^{-1} a^{-1} (Forte et al., 2004). The current consumption (estimated from data obtained by interviewing key operators in the region) is somewhat lower, 200 bricks person^{-1} a^{-1}, due to changes in the type of buildings and construction techniques. Earlier, solid bricks were primarily used, whereas hollow bricks are used predominantly at present. The production of hollow bricks requires about 0.3–0.4 m^3 of soil (depending on the composition of the soil and the amount of waste).

In their analysis, Rivas et al. (2006) showed that the 'human geomorphic footprint' (area affected and volume mobilised) produced by this industry in the area was 5.6 m^2 person^{-1} a^{-1} and 3.7 m^3 person^{-1} a^{-1}, respectively. The values for 2006–2012 were 5.7 m^2 person^{-1} a^{-1} and 4.8 m^3 person^{-1} a^{-1}, respectively (Hurtado, 2015). Of the total area affected, almost 90% corresponded to decapitation, although deep excavations have increased recently. The distribution of these areas is shown in Fig. 5. The environmental impact of increasing, widespread excavations surrounding urban areas has been described for this and other regions (Pereyra and Rimoldi, 2003; Pereyra, 2004; Subba Rao and Prathap Reddy, 2004; Rivas et al., 2006; Jordan, 2009; Zuquette et al., 2009; Dal Sasso et al., 2012; Hurtado, 2015). The impact on the humid Pampa includes:

- High-quality soils are lost and productivity sharply declines due to decapitation. Giménez et al. (2002) revealed an up to 95% reduction in productivity. Nearly 250 km^2 (40% of the total) of the best-quality soils (capability classes I–III; Klingebiel and Montgomery, 1961) around La Plata were lost between 1882 and 2001, half of which accounts for the impact of soil mining (Forte et al., 2004; Hurtado et al., 2008).
- The pollutant-retention capability of soils is reduced and the risk of groundwater pollution increased (Pereyra and Rimoldi, 2003; Pereyra, 2004; FrePlata, 2012; Angheben, 2013).
- Abandoned hollows are formed, with uncontrolled dumping of different, often polluting, types of waste (FrePlata, 2012; Angheben, 2013).
- Stagnant waters are accumulated, with consequent risk of vector-borne disease and drowning. At least 41 deaths have been reported in these abandoned excavations between 1980 and 2011 (Hurtado, 2015). Data on vector-borne diseases have not been collected systematically, although public health personnel in the area has indicated the prevalence of intestinal diseases and other infectious diseases in these areas.
- Lastly, the visual landscape is degraded.

3. Methodology

The methodological approach involved the following steps: A). *Characterisation of sediments and assessment of suitability*. Lakes with sediments as suitable raw material for brick making (surface clayey sediments with similar qualities to currently used soils) were identified. The lakes were selected for sampling and the sediment composition was initially determined. The test bricks were investigated and their technical properties determined. B). *Assessment of resources*. The

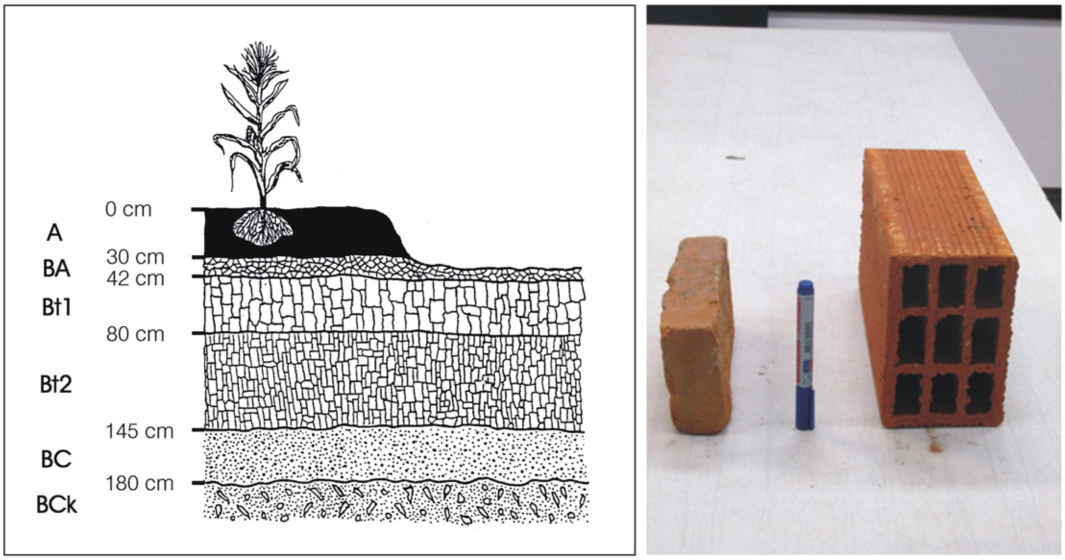

Fig. 3. Typical soil profile of an argiudol and types of bricks made from the A and B horizons. Horizons A and BA used for solid bricks. Horizons Bt1 and Bt2 used for hollow ones.

Fig. 4. Examples of abandoned exploitations. Left: deep excavation for extraction of sub-base and other construction materials (water accumulation can be observed). Right: A horizon decapitation for brick manufacture, showing desiccation cracks in the B horizon. Observe the difference with non-decapitated terrain in the background.

sediment sequence, especially the thickness of the potentially suitable surface layer, was determined. The existing resources were estimated. C). *Assessment of renewal potential.* The erosion and sedimentation rates were analysed and the deposit-renewal rate estimated.

A. An initial survey based on some former studies (Dangvas and Blasi, 2002; Dangavs et al., 2006; Dangavs, 2008, Dangavs and Reynaldi, 2008; Dangavs, 2010) was performed, including satellite images and air-photo interpretation. Initially, 95 lakes, 'bañados' and river sectors were identified (Table A; supplementary information). Upon further investigation, 61 were discarded for various reasons, such as high salt or sand content in the sediments or accessibility problems. The remaining water bodies and the analytical methods are listed in Table 1. Ninety-six samples were collected for the characterisation of sediments in terms of the grain size distribution and Atterberg limits. The 'bañados' were extracted during the dry period, using a shovel. In the lakes, short cores were extracted with polyvinyl chloride (PVC) tubes. Based on the data and results thus obtained, a series of lakes and 'bañados' in two study areas (Fig. 6) were selected for the preparation of ceramic pastes and test bricks. Furthermore, to test the suitability of lower-quality sediments (with higher sand content), samples were collected from lakes in a third area (Junín, Fig. 6). The grain size (Kilmer and Alexander, 1949) and Atterberg limits were analysed in detail for these pastes and for commercial pastes.
The test bricks were prepared using sediment samples (either pure or mixed in different proportions), as well as commercial ceramic pastes, to determine the following properties: water absorption capacity, compressive strength and frost behaviour. Analyses were performed according to the IRAM 12566–1 (IRAM. http://www.iram.org.ar/) and CIRSOC 501 (INTI, 2007) guidelines, and the results were compared with the norm requirements.
B. The sedimentary sequences in the lakes were obtained from the literature, including previous works by some of the authors (Doering, 1884; Ameghino, 1889, 1884; Valentín, 1898; Frenguelli, 1957; Fidalgo et al., 1975; Dangavs, 1979; Riggi et al., 1986; Dangvas and Merlo, 1994; Dangvas and Blasi, 1994; Iriondo and Kröhling, 1995; Dangvas and Merlo, 1997; Dangavs and Blasi, 2003, 2002; Dangavs et al., 2006; Dangavs, 2008, Dangavs and Reynaldi, 2008; Dangavs, 2009a,b,c, Dangavs and Mormeneo, 2012; Dangavs and Pierrard, 2013), or they were determined by manually extracting the sediment cores. The maximum water depth in these lakes rarely exceeds 1.5 m, which is <1 m in most cases. The thickness of the alluvial (Ameghino, 1889, 1884; Valentín, 1898) and suballuvial (Doering, 1884) sediment layers in the lakes does not typically exceed 1.5 m, the average being approximately 60 cm. Sediments below these two units – the Luján, La Postrera, Ensenada and Buenos Aires formations (Frenguelli, 1957; Fidalgo et al., 1975; Riggi et al., 1986; Iriondo and Kröhling, 1995) – correspond to fluvial, fluviomarine or aeolian deposits that are unrelated to the present sedimentation. The sediment volume was calculated from data on the area of the lake and thickness of the alluvial plus suballuvial layers. The obtained results were extrapolated to estimate the potential resources in the entire region.
C. The renewal rates of lake sediments were estimated based on two types of data. On the one hand, the age of the alluvial deposits was obtained from the literature, based on which the average sedimentation rates for the period were estimated. On the other hand, the recent erosion rates in the region were also obtained and estimated from the literature. They were used to estimate sediment generation within the lakes' basins and their consequent sediment supply. As expected from previous results (Bonachea et al., 2010; Bruschi et al., 2013), the latter data yielded significantly higher potential sedimentation rates than the former.

4. Results and discussion

4.1. Characteristics of the sediments

A typical cross section of lake sediments is shown in Fig. 7. The thickness of the suitable surface layer is 0.3–1.0 m. Table B (supplementary information) presents the grain size and Atterberg limits analysed for the extracted samples. Of 96 samples, only nine were unsuitable for preparing ceramic pastes, either directly or in combination with materials available in the surroundings (a common practice in the local industry). Tables 2A and 2B present the results of the analyses of ceramic pastes made with sediments and commercial pastes, respectively.

Fig. 8 shows the grain size distribution of the sediment samples and of the commercial ceramic pastes. In Fig. 9, the grain size analyses of ceramic pastes are presented in more detail. Some pastes made directly with the sediment have adequate grain size: LSV1 (a mixture of dredge spoil from the lake) and LSV2 (a mixture of sediment samples extracted from the lake). Mixes prepared with sediments from nearby sources were adequate in certain cases (B, B2, C, D, LCRS1 and LCRS2), whereas others were not (LCG1, LCG2, LCG3, LCRS3 and LCRS4, all originating from the Junín area). Finally, mixes C1–5 and D1–5 prepared with sediment and different proportions of fine fluvial sand, equivalent to that from the Rio de la Plata, in the neighbouring area of Magdalena (C1–5 and D1–5), were also found to be adequate.

Table C (supplementary information) summarises the water absorption capacity, resistance to frost and compressive strength

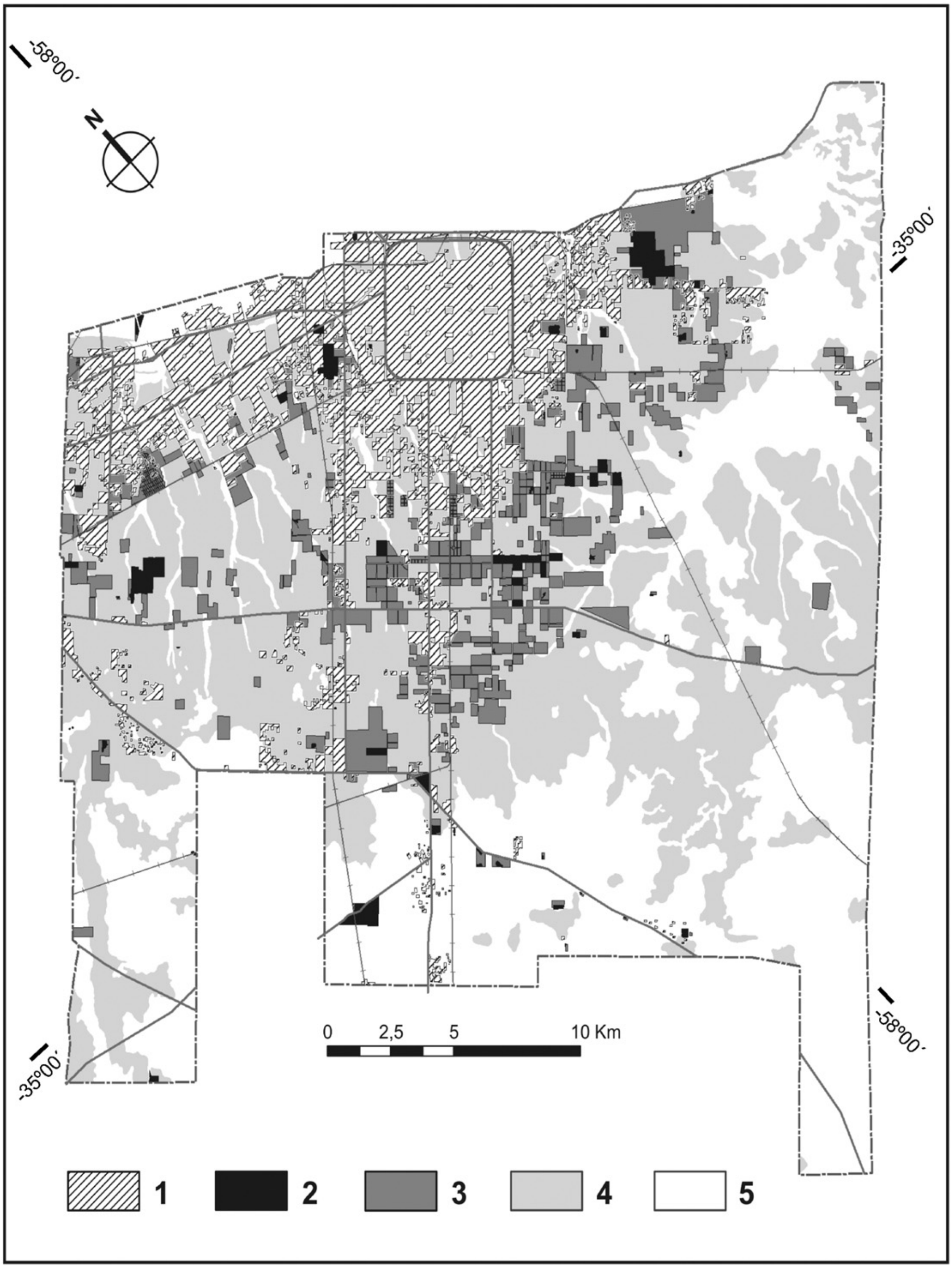

Fig. 5. Map showing areas affected by different types of soil/subsoil mining around La Plata. 1: Built up areas. 2: Deep excavations. 3: Soil decapitation. 4: Capability classes I, II and III. 5: Soils of lower capability class.

determinations. The experimental pastes were found to have 11–15% water absorption capacity, whereas commercial pastes yielded worse values of 19–26%. The compressive strength was estimated to be 129–141 kg cm^{-2} for experimental pastes and 74–120 for commercial pastes, which were also worse. Even at higher temperatures ranging from 800 and 900 °C, experimental pastes had superior values to commercial pastes. The frost resistance was adequate in all cases. The properties of the majority of test bricks fall within the norm limits (IRAM, INTI, 2007), even at lower oven temperatures, including bricks with high content of fine fluvial sand (C4–5 and D4–5). The only exceptions are mixes prepared with sediments from the Junín area, as expected based on the data in Table 2A. Nevertheless, the values do not exceed these norm limits much and are superior to those obtained for the majority of bricks made with commercial pastes.

Bricks made with lake sediments are expected to yield similar (or even better) results than commercial bricks. As indicated earlier, the surface layer used has formed (and is presently forming) by the accumulation of sediment eroded from the A and B soil horizons, the layers exploited by the brick industry.

Table 1

Lakes, "bañados" and river sectors for which determinations were carried out. A: sampling and grain size analysis (Shepard). B: grain size analysis (Winkler). C: Elaboration of pastes and determination of Atterberg limits. D: Elaboration of test bricks and determination of technical properties. E: Estimation of erosion/sedimentation rates. Lake numbers as in Table A and Fig. A (supplementary information). In the case of river sectors (numbers 4, 12, 26, 46, 47 and 48), coordinates of sampling points are indicated in Table A.

Lake/"bañado"/river and (N°)	Determinations	Area (ha)	Area basin (ha)	Thickness Alluvial (m)	% suitable	Estimated exploitable volume ($\times 10^3$)	Thickness Suballuvial (m)	% suitable	Estimated exploitable volume ($\times 10^3$)
Laguna de Gómez (2)	A, C, D	5200	–	–	–	–	–	–	–
Laguna del Carpincho (3)	A, C, D	425	–	–	–	–	–	–	–
Rio Salado (upstream Laguna Carpincho; 4)	A, C, D	–	–	–	–	–	–	–	–
Laguna Tacurú (9)	A, B, C, D, E	156	14,530	0.5	100	780	0.7	100	1092
Laguna La Bellaca (10)	A, B, C, D, E	65		0.5	100	325	0.7	100	455
Laguna San Vicente (11)	A, B, C, D, E	178		0.6	100	1068	0.7	100	1246
Arroyo San Vicente (downstream Laguna San Vicente; 12)	A, C	–	–	–	–	–	–	–	–
Laguna Vitel (49)	A, C, E	1470	51,700	0.6	50	4410	0.6	50	4410
Arroyo Vitel (50)	A, C	–	–	–	–	–	–	–	–
Laguna Chascomús (51)	A, C	3012		–	–	–	–	–	–
Laguna Manantiales (57)	A, C	–	–	–	–	–	–	–	–
Laguna Del Burro (56)	A, C, E	1005	9900	0.5	50	2512	0.3	50	1508
Laguna Adela (55)	A, C, E	2085	8900	0.5	50	5212	0.7	50	7298
Laguna Chis Chis (58)	A, C	1470		0.4	50	2867	0.5	50	3675
Laguna La Salada (66)	A, C	–	–	–	–	–	–	–	–
Laguna San Juan de la Leña (43)	E	238	2131	0.4	50	476	0.7	50	833
Laguna Espadaña de Pérez (45)	E	290		0.4	50	580	0.7	50	1015
Laguna Chica (44)	E	75		0.4	50	525	0.7	50	263
Laguna Cildañez (42)	E	297		0.4	50	194	0.7	50	340
Laguna Quinteros (37)	E	330	9019	0.3	50	495	0.4	50	660
Laguna del Medio (39)	E	546		0.65	50	1776	0.63	50	1721
Laguna Esquivel (41)	E	2453		0.65	50	7973	0.63	50	7728
Laguna El Espartillar (38)	E	1252		0.65	50	4071	0.63	50	3945
Bañado La Yalca (67)	A, C	879	–	1	100	8973	*	*	*
Bañado La Libertad (68)	A, B, C, D	348	–	1	100	3484	*	*	*
Bañado Don Mario (69)	A, B, C, D	606	–	1	100	6059	*	*	*
Bañado La Eloísa (72)	A, B, C, D	756	–	1	100	7564	*	*	*
Bañado San Juan de María (71)	A, B, C, D	814	–	1	100	8144	*	*	*
Bañado Miraflores (70)	A, B, C, D	630	–	1	100	6304	*	*	*
Laguna Las Perdices N (18)	A, C	825	–	0.45	50	1856	0.45	50	1856
Río Salado (upstream National Route N° 3; 26)	A, C	–	–	–	–	–	–	–	–
Río Salado (downstream city of Gral. Belgrano; 46)	A, C	–	–	–	–	–	–	–	–
Río Salado (downstream city of Gral. Belgrano; 47)	A, C	–	–	–	–	–	–	–	–
Río Salado (downstream city of Gral. Belgrano; 48)	A, C	–	–	–	–	–	–	–	–

4.2. Assessment of resources

The amount of sediment available was estimated based on the data in Table 1. As presented in the table, the total area of the lakes and 'bañados' is approximately 250 km^2. The area of water bodies with suitable sediment, as indicated by the data, is approximately 150 km^2 (105 km^2 of which correspond to bodies with experimental data obtained for this work). That is, 60–40% of the lakes and 'bañados' analysed have sediments that can be used to manufacture bricks. In certain cases (for instance, Tacurú, La Bellaca and San Vicente and all 'bañados'), all of the alluvial and suballuvial units are suitable for brick making. However, in other lakes, the sediments around the outer parts are coarser grained and of lower quality. Therefore, only 50% of the materials in the latter can be used for brick making, a very conservative estimate (see Table 1).

If the proportion (40% in a conservative estimate) of lakes and 'bañados' with suitable sediment was the same for the entire province and the study area, the potentially suitable area would be >1500 km^2. However, the selection of water bodies considered here is somewhat biased. Therefore, a conservative extrapolation was made, considering that only 20% of the lake/'bañado' area in the province (900 km^2) is likely to contain exploitable resources. For a more conservative and careful estimate, the total area with characteristics similar to those described here is unlikely to be <500 km^2. Considering an average thickness of 60 cm for alluvial plus suballuvial sediments, and that only 50% would be adequate, we obtain a total of 300 × 10^6 m^3. With the present consumption rate of 200 bricks person^{-1} a^{-1} (0.3–0.4 m^3 person $^{-1}$ a^{-1}), this can sufficiently supply the city and province of Buenos Aires (approximately 19 million people) for a period of 40–50 years.

It is given that these sediments are extracted, if possible, from specific locations, which have been thoroughly analysed for their technical, environmental and economic feasibility. To further asses the feasibility of exploiting lake sediments, two lake/'bañado' complexes were analysed in detail, as well as three lakes in the San Vicente area (San Vicente, La Bellaca and Tacurú), and the Don Mario, La Libertad and Laguna La Yalca 'bañados', in Chascomús (Fig. 6). This analysis was undertaken at the request and with the cooperation of local entrepreneurs seeking to exploit this potential resource. The first complex covers 399 ha. The average sediment thickness (both alluvial plus suballuvial suitable for brick making) is 1 m and the total volume 4 × 10^6 m^3. As 1 m^3 of material is needed to produce 600 bricks, 2.4 × 10^9 bricks are manufactured. This is equivalent to 250 years' worth of production of one of the large brick industries in the region. In the Chascomús area, to obtain material of brick-making quality, the 'bañado' sediments (clay rich) must be mixed with lake sediment (silt–sand rich) in the proportion 80/20%. This type of mixing is a common practice in the local industry. The thickness of suitable sediments is 1 m in the 'bañados' (650 ha) and 0.25 m in the lake (950 ha). Upon mixing the entire 'bañado' sediment with approximately half of the lake sediment, a total of 4.7 × 10^9 bricks can be produced, equivalent to 500 years' worth of production of one of the many large local industries. In spite of assuming a large error in the presented estimates, these sediments represent an interesting potential resource.

Although this analysis indicates the feasibility of exploiting this potential resource, additional and more in-depth analyses in specific,

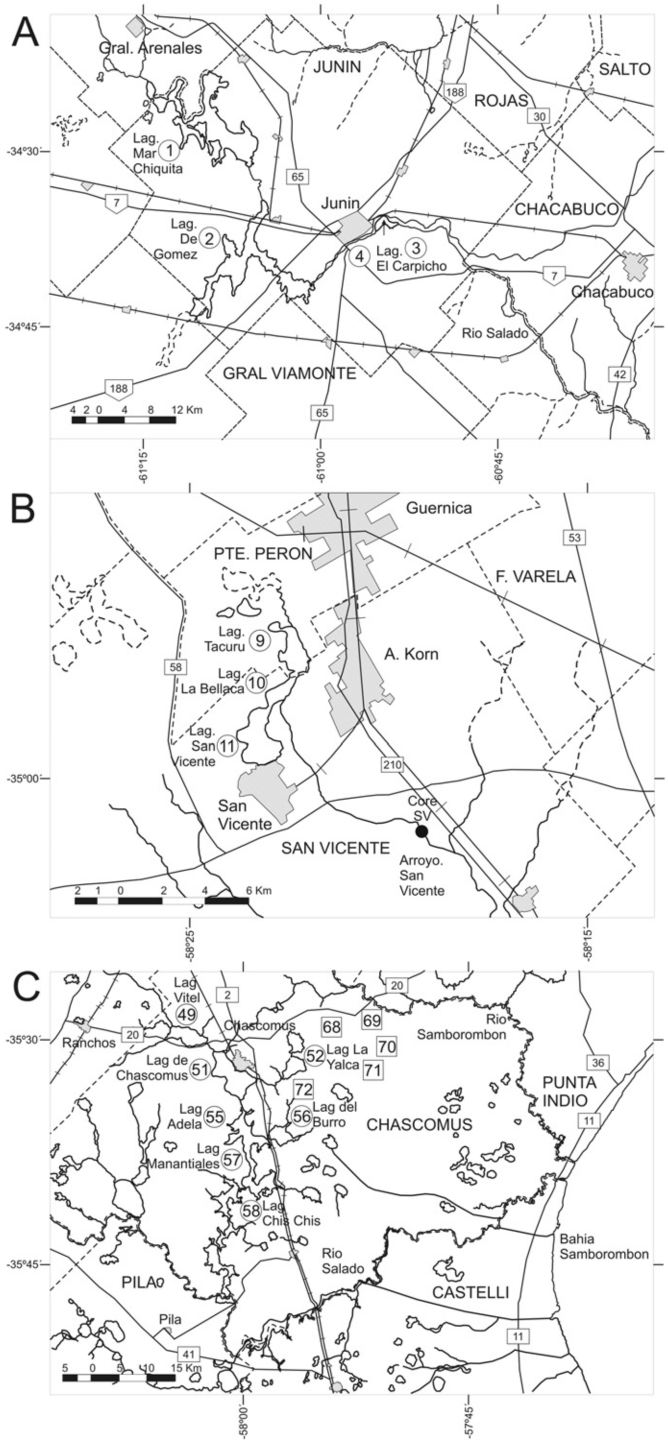

Fig. 6. Location of the three areas selected (see Fig. 1 and A) for the extraction of sediment and elaboration of test bricks. Lake (circles, names) and "bañado" (squares) numbers correspond to the ones in Table A. Location of core sampling point in Arroyo San Vicente (Core SV) is shown in 6B.

selected water bodies are needed. Other factors, such as mining and transport costs and environmental constraints for the new means of exploitation, must be considered before determining the feasibility. In a preliminary analysis of 'bañados', the excavation costs may be the same as that of the present methods of extracting soil. This is because extraction can easily be performed during the dry period, using the same techniques. Its impact on the soil and productive activities would, in principle, be lower, because these areas have low-quality and are only used as low-intensity pasturelands.

4.3. Assessment of renewal rate

The recent increase in sedimentation rates observed in the region has led to the filling of several lakes, which have been transformed into intermittent wetlands or 'bañados'. For instance, Laguna Chica and Laguna Espadaña de Pérez have been completely filled (Fig. A; supplementary information). Other lakes, such as Quinteros, Monte, Las Perdices, Adela, Cerrillo del Medio, Tacurú, La Bellaca and San Vicente (Fig. 6 and Fig. A; supplementary information), are at an advanced stage of infilling (Dangvas and Merlo, 1997, 1994; Dangavs and Reynaldi, 2008; Dangavs and Mormeneo, 2012; Dangavs and Pierrard, 2013). Thus, the sediment accumulation rate may be comparable to the current exploitation rate.

The thickness of the suballuvial and alluvial formations described in Section 2.2 was obtained from the literature (Dangavs, 1979, 2009a,b,c, 2008, 2005; Dangavs and Blasi, 2003, 2002; Dangvas and Merlo, 1994, 1997, 1994; Dangavs et al., 2006; Dangavs and Reynaldi, 2008; Dangavs and Mormeneo, 2012; Dangavs and Pierrard, 2013) and from field surveys. The accumulation period was considered to be 700 years for the suballuvial and between 300 (earliest proposed limit for the LIA) and 200 (start of extensive European occupation) years for the alluvial. Based on these age estimates, average sedimentation rates of 0.8 mm/year for the suballuvial and 1.6–2.4 mm/year (300–200 years) for the alluvial were obtained.

Table D (supplementary information) presents data and estimates of the current erosion rates in the region, as obtained from the literature. The rates are in the order of 1–1.5 mm/year in farmland–pasture areas with a gradient of <0.5° (Michelena et al., 1988, 1991; Bujan et al., 2003; Frank and Viglizzo, 2010; Kraemer et al., 2013) and approximately 0.3 mm/year in completely flat areas with nearly natural vegetation or pastures (Michelena, 2014). The potential erosion rate (depending on local conditions as well as land use and management factors) is estimated to be 0.3–3.7 mm/year. As the lower limit represents highly infrequent conditions, actual erosion is likely to occur a bit more frequently. Therefore, sediment generation under the present (and presumably near-future) conditions ranges from 300 to 3700 $m^3\ km^{-2}\ a^{-1}$. These values were used to calculate the potential sediment generation in a series of lake basins, for which the watersheds could be determined. Oftentimes, this calculation is difficult, due to the extremely low gradients in the region. Table 3 summarises the results.

The data in Table 3 indicate that the area of the 14 lakes considered is just over 100 km^2. The estimated sedimentation rates for these lakes vary widely (1–140 mm a^{-1}), but the total annual sedimentation is found to range from 300,000 to 3,800,000 m^3/year. This is based on the assumption that all generated sediment is carried into the basin and that the density of both the eroded topsoil and sediment accumulated in the lake is 1 t m^{-3}. However, these assumptions are only a rough approximation. Using the densities determined for both types of materials (an average of 1.1 t m^{-3} for the topsoil and 1.65 t m^{-3} for the sediment), the rates obtained would be in the order of 200,000–2,500,000 m^3/year. Further, given that only half of the sediment generated in the basin is actually carried into the lake (although eventually most of it will be), the amount of material accumulated annually in the 14 lakes is estimated to be 100,000–1,250,000 m^{-3}. This is equivalent to the needs of 300,000–4,000,000 individuals at the present consumption rates. If the estimates for the analysed area (5–6% of the total lake/bañado area in the region) are extrapolated to the whole humid Pampa, the annual supply of sediment of brick-making quality can cover the needs of a significant proportion of the population in the city and province of Buenos Aires.

An independent observation in Arroyo San Vicente (Fig. 6), which connects Laguna San Vicente to a 'bañado', offers an indirect method of assessing the reliability of the previous estimates. As shown in Table 3, the sedimentation rates for Laguna San Vicente are estimated to be 10–135 mm a^{-1}. The Arroyo San Vicente was dredged in 2003, wherein the sediment layer on top of the 'Pampean' unit

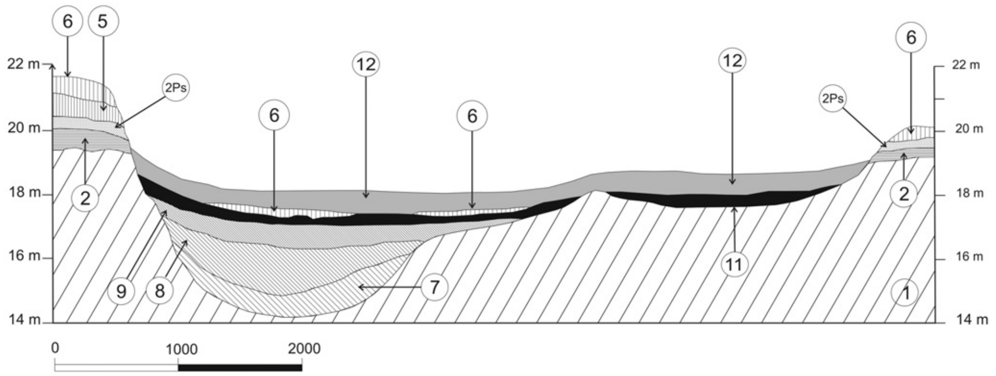

Fig. 7. Example of a cross section of the sediment sequence, in Laguna Las Perdices. 1: Ensenada Formation. 2: Buenos Aires F. 2ps: un-named paleosols. 3: Luján F., La Chumbiada member. 5: Luján F., Lobos member. 7: Lujan F., Rio Salado member. 8: La Postrera III. 9: Suballuvial. 10: La Postrera IV. 11: Alluvial.

(easily recognisable due to its reddish colour and greater compaction) was removed. The present sediment thickness in a recently extracted core (core SV, Fig. 6B) is estimated to be 17 cm, equivalent to 15 mm a^{-1}, which is somewhat higher than the lower estimate mentioned above. The grain size and Atterberg limits for the sediment in this core are as follows: <2 μ, 36.59; 2–20 μ, 39.63; >20 μ, 23.78 (36/40/24); LL, 40.25; LP, 20.78; and PI, 19.47 (40/21/19). These values represent the optimum conditions for ceramic use, thus confirming the studied sediment to be a potential resource. The sampling point was located in a channel affected by stream flow and downstream of three lakes (Tacurú, La Bellaca and San Vicente) with shallow waters and abundant vegetation. It follows then that most of the sediment is deposited in the lakes and the sedimentation rates are significantly higher.

Table 2A
Grain size distribution (Kilmer and Alexander, 1949) and Atterberg limits of experimental pastes.

	Grain size distribution % 2 μ/2–20 μ/>20 μ	Atterberg limits LL/PL/PI
LCG1	15/13/72	33/23/10
LCG2	16/12/72	38/26/12
LCG3	7/18/75	26/nd/nd
LCRS1[a]	17/14/68	35/23/12
LCRS2[a]	18/16/66	40/25/15
LCRS3	11/17/72	30/nd/nd
LCRS4[a]	6/18/76	25/nd/nd
LSV1[a]	18/26/56	28/25/3
LSV2[a]	29/21/50	36/23/13
B	35/19/46	55/23/32
B2[a]	30/14/56	38/16/22
C	50/21/29	37/44/23
C1	47/25/28	63/24/39
C2	40/15/45	50/21/29
C3	34/13/53	44/17/27
C4[a]	28/11/60	38/14/24
C5[a]	25/10/65	30/14/16
D	46/25/29	62/28/34
D1	44/16/40	59/25/34
D2	40/12/42	51/23/28
D3	35/13/52	40/21/19
D4[a]	29/13/58	36/17/19
D5[a]	23/11/66	29/14/15

LCG. Mix of sediments from Laguna del Carpincho (3) y Laguna de Gómez (Junín; 2).
LCRS.1, 2, 3, 4. Mixes of silty sediments from Laguna del Carpincho (3) and silty-sandy sediments from the Rio Salado (Junín; 26).
LSV1. A mix of sediments dredged from Laguna San Vicente (11) and accumulated near its margin.
LSV2. Sediments from Laguna San Vicente (11).
B. Mix of sediments from the "bañados" D. Mario (69), La Libertad (68), San Juan de María (71), La Eloisa (72) and Miraflores (70; Chascomús).
B2. The same mix of "bañado" sediments, with silty-sandy sediment from Laguna La Yalca (52; Chascomús).
C: Sediments from Bañado de Don Mario (69; Chascomús).
D. Sediments from Bañado La Libertad (68; Chascomús).
C1–5 and D1–5 correspond to mixes of sediments from the "bañados" with progressively greater proportion of fine fluvial sand (10–50%).
LL: liquid limit. PL: plastic limit. PI: plasticity index.
[a] Pastes selected for the elaboration of test bricks.

Thus, the present (and near-future) sedimentation rates are approximately one order of magnitude greater than those registered for the alluvial layer and, in turn, twice that for the suballuvial layer. This increase is most likely due to the increasing human modification of the land surface (Walling, 2006; Tarolli and Sofia, 2016), reflecting a progressively greater, human-induced geomorphic change. The results presented here are in line with the concept of a 'great geomorphic acceleration' (Bruschi et al., 2012a,b, 2013) after the mid-20th century, which coincides coinciding with the 'Great Acceleration' that marks the start of the Anthropocene (Steffen et al., 2015; Waters et al., 2016).

Table 2B
Grain size distribution (Kilmer and Alexander, 1949) and Atterberg limits of commercial pastes.

Commercial	Grain size distribution % 2 μ/2-20 μ/>20 μ	Atterberg limits LL/PL/PI
LP1	25/31/44	44/25/18
LP2	32/27/41	35/23/12
BR1	33/26/41	43/24/19
BR2	25/38/37	39/24/15
BR3	26/35/39	44/29/15
BR4	26/37/37	42/27/15
FV1	24/28/48	47/26/21
FV2	26/38/36	39/25/14
FV3	34/31/35	42/27/15
LH1	39/22/39	52/27/25
LH2	16/31/53	41/22/19
EZ1	27/36/37	40/21/19
EZ2	26/35/39	41/22/19
EZ3	25/39/36	47/26/21
EZ4	27/38/36	50/25/25
CA1	33/30/37	40/22/18
CA2	37/18/45	38/21/17
CA3	29/24/47	43/26/17
CA4	18/35/47	45/22/23
CA5	35/15/50	42/24/18
CA6	34/26/40	45/25/20
MP1	29/29/42	47/22/25
MP2	12/58/30	47/23/24
MP3	33/29/38	47/22/25
MP4	18/41/38	46/20/26
MP5	24/39/37	53/23/30
MP6	24/44/32	48/24/24
MP7	23/25/52	48/24/24
MP8	29/31/40	50/22/28
MP9	25/32/43	49/23/26

Ceramic pastes obtained from industrial establishments of the following localities: LP: La Plata; BR: Brandsen; FV: Florencio Varela; LH: Las Heras; EZ: Ezeiza; CA: Cañuelas; MP: Marcos Paz. LL: liquid limit. PL: plastic limit. PI: plasticity index.

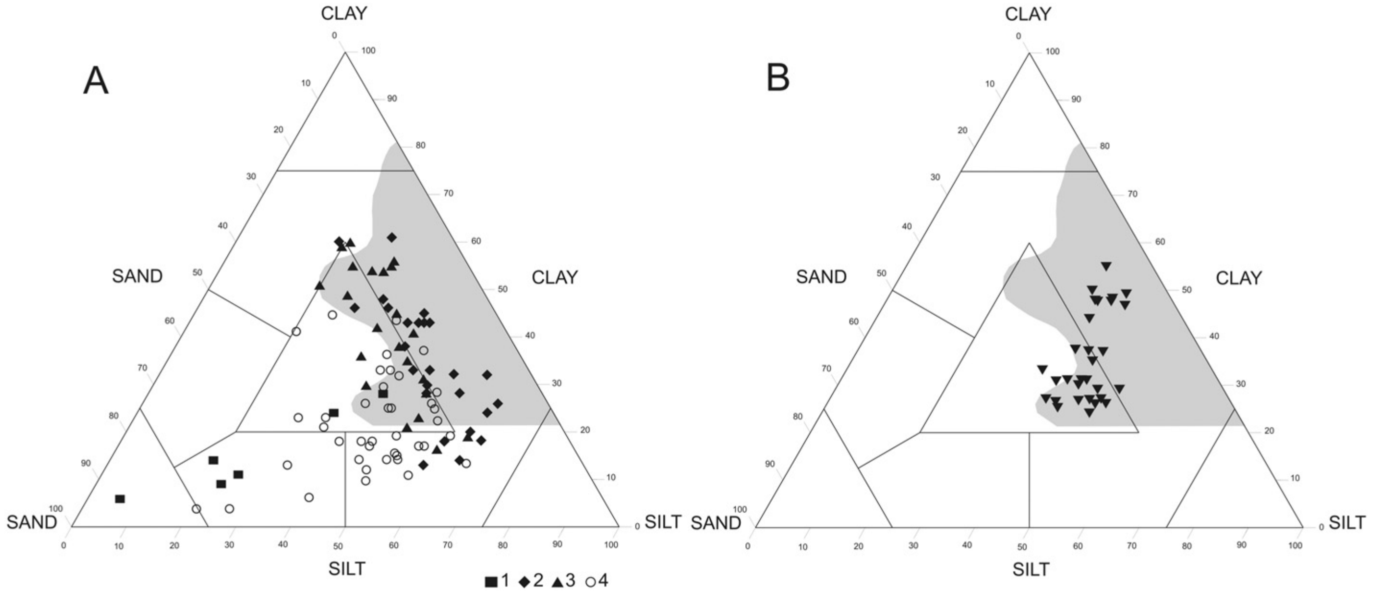

Fig. 8. Shepard's (1954) diagram, showing the grain size distribution of samples obtained. Shaded, aptitude field defined by Fabbri and Dondi (1995). A. Grain size of lake sediments from the different study areas (Fig. 7). 1: Sediments from Junín. 2: Sediments from San Vicente. 3: Sediments from Chascomús. 4: Sediments from other areas, not used for making pastes. B. Grain size of ceramic pastes from the brick industry.

5. Conclusions

The results show that the majority of the sediment recently accumulated in the lakes of the humid Pampa are similar or superior to the topsoil currently used for brick making in terms of composition and properties. In addition, the existing resources are likely to adequately cover the needs of the industry for several decades, and the sediment is presently accumulating at a rate comparable to the current exploitation rates. Thus, sediments from lakes and swampy areas represent a practical alternative to soil mining, thus potentially eliminating this type of activity, and its related environmental impacts.

The recent increase in the sedimentation rate seems to reflect the anthropogenic geomorphic change (the great geomorphic acceleration characterising the Anthropocene?) affecting the Pampa region. The rates were much lower in earlier historical periods, more so before European settlement and modification of surface geologic processes.

If the present results are confirmed by the new study under way, this economic activity can be made more efficient and sustainable. Due to the several lakes and 'bañados' in the region, sufficient resources of good quality to cover the needs of the industry for many decades (perhaps centuries) are highly likely to be present. Moreover, human-enhanced erosion in the region may increase the sedimentation rates,

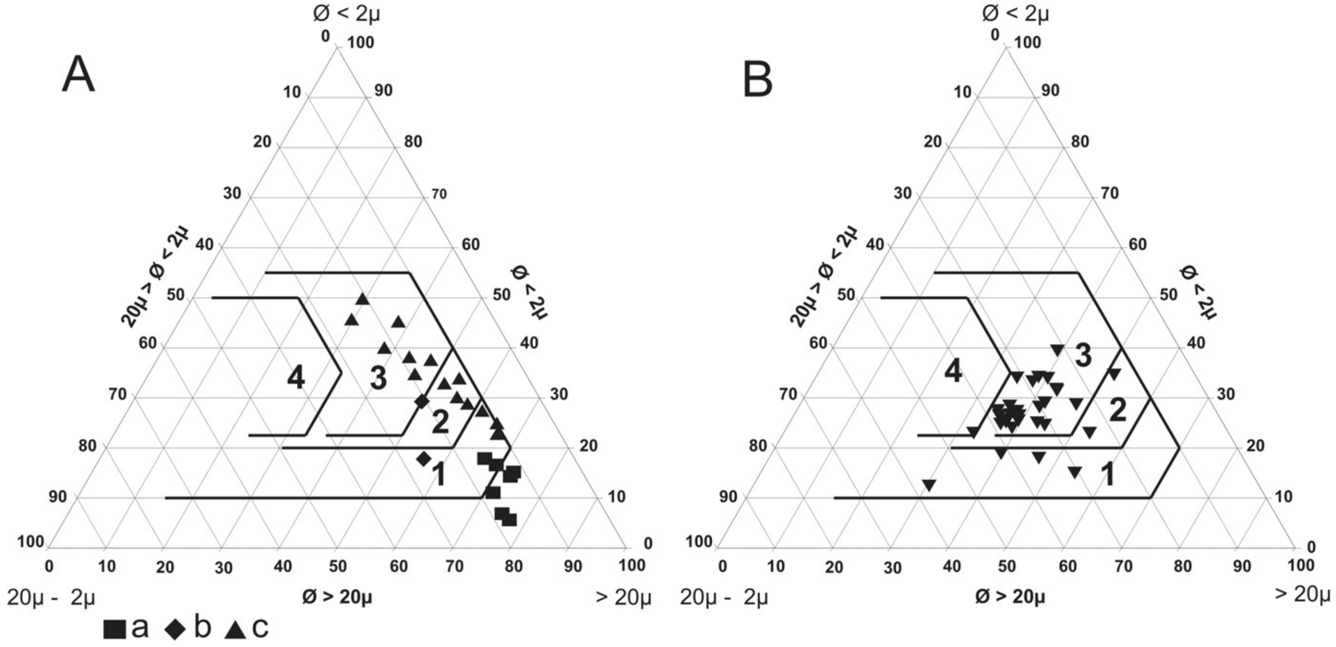

Fig. 9. Winkler (1954) diagram showing grain size distribution of samples and quality fields for different types of ceramic pastes. a) Pastes made with Junín sediments. b) Id. San Vicente. c) Id. Chascomús. 1: Quality field for common bricks. 2. Id. Vertically perforated bricks. 3: Tiles and light blocks. 4- Blocks and hollow bricks.

Table 3
Estimates of sediment generation and accumulation in several basins/lakes. The range of erosion rates considered is 0.3–3.7 mm·a^{-1}. Sources and information used for the calculations are presented in Table D (supplementary information).

Lake (N°)	Area basin (ha)	Area lake (ha)	Sedimentation rate (max/min mm·a^{-1})	Total volume (max/min 10^3 m^3·a^{-1})
Vitel (49)	51,700	1470	143.7/11.7	2112/172
Adela (55)	8900	2085	15.8/1.3	329/27
del Burro (56)	9900	1005	36.4/3	365.8/30.2
SJ de la Leña (43)	2131	238	11.3/0.9	26.9/2.1
Espadaña de Pérez (45)		290		32.8/2.6
Chica (44)		75		8.5/0.7
Cildañez (42)		297		33.6/2.7
Quinteros (37)	9019	330	7.3/0.6	24.1/2
del Medio (39)		546		39.9/3.3
Esquivel (41)		2453		179.1/14.7
El Espartillar (38)		1252		91.4/7.5
Tacurú (9)	14,530	156	134.7/10.9	210.1/17
La Bellaca (10)		65		87.6/7.1
San Vicente (11)		178		239.8/19.4

making lake sediments a renewable resource. The method presented can be applied to other large plains that lack materials for construction but is commonly exploited for brick making. Research is currently under way to analyse thoroughly and further assess the resource potential of the two locations.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catena.2016.02.006.

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