Quaternary alluvial fans of Ciudad Juárez, Chihuahua, northern México: OSL ages and implications for climatic history of the region

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Resumen

Los abanicos aluviales que subyacen dentro de la zona urbana de Ciudad Juárez, al Norte de México, son afectados en su desarrollo de manera relevante. Al norte de la ciudad, estos son más activos pero los más antiguos están al sur donde la ciudad se desarrolló. Este sistema, está erosionado tanto por procesos naturales, como por la modificación debido a la urbanización. Se recolectaron tres muestras de arena eólica donde se localizan los abanicos más recientes. Las edades mínimas de estos abanicos cuaternarios fueron determinados mediante Luminiscencia Óptica Estimulada (OSL por sus siglas en Inglés) y fueron: a) P1; 31,000 años; b) P2; 41,000 años; c) P3; 74,000 años; estas están en los rangos de etapas de isotopía de oxigeno (OIS 3-5 por sus siglas en Inglés) y resultaron más antiguas de lo esperado. Estos abanicos sirven ahora como basamento de la ciudad y terminaron en el Pleistoceno Tardío, justamente después de lo que se interpretó como un intenso período de erosión, sin más depósito durante el Pleistoceno Tardío - Holoceno. Las tres dataciones corresponden a periodos glaciales globales correspondientes a periodos secos y fríos, que produjeron el transporte de arenas eólicas en el norte de México. Posteriormente se produjeron fases de clima húmedo que activó la erección de los abanicos. Estos, se intercalan con sistemas fluviales y terrazas derivadas del Río Bravo, lo que indica una componente de disección debido a la erosión lateral del Río que estuvo activa durante edades tempranas a las registradas en las muestras datadas (OSL). Sin embargo, esto no está aún determinado y se requiere una futura datación del sistema de abanicos.

Palabras clave: Luminiscencia, Norte de México, Ciudad Juárez, Abanicos aluviales, Cuaternario.

Abstract

Alluvial fans formed from erosion of the Juárez Mountains in northernmost México have a significant flood impact on the city of Juárez, which is built on the fan system. The northern part of Ciudad Juárez is the most active; further south, older parts of the fan, upon which the rest of the city is built, were largely eroded by natural processes prior to human habitation and subsequently modified only recently by human construction. Three Aeolian sand samples, collected from the uppermost (youngest) parts of the fan system in the city area, in places where human intervention has not disturbed the sediment, constrain the latest dates of fan building. Depositional ages of the Quaternary alluvial fans were measured using Optically Stimulated Luminescence (OSL) on Aeolian sands that have inter-fingered with alluvial fan material. These dates are: a) Sample P1: 31 ka; b) Sample P2: 41 ka; c) Sample P3: 74 ka, between Oxygen Isotope Stages 3 to 5. They demonstrate that fan development, in the area now occupied by the city, terminated in the late Pleistocene, after which we interpret an extended period of erosion, without further deposition, lasting from the late Pleistocene to Holocene. The three dates broadly correspond to global glacial periods, implying that the cool, dry periods may reflect periods of Aeolian transport in northern México in between phases that were wetter to form the alluvial fans. Alluvial fan margins inter-finger with fluvial terrace sediments derived from the Rio Bravo indicating an additional component of fan dissection by Rio Bravo lateral erosion, presumed to be active during earlier times than our OSL ages, but these are not yet dated. Further dating is required to ascertain the controls on the fan and fluvial system.

Key Words: Luminescence, northern México, Ciudad Juárez, alluvial fans

1. Introduction, previous research, and study purpose

The alluvial fan system located beneath and around the city of Juárez, Chihuahua, northern México (Fig. 1) is part of a late Tertiary to Quaternary development throughout the southwestern USA and northern México region. Much research has been published (in the USA) about the history of the Rio Grande, with key papers published by Hawley *et al.* (1976) and Mack *et al.* (2006). However, there is poor knowledge of the southern continuation of the system into northern México where the Rio Grande is called the Rio Bravo. This paper presents the first attempt to link the chronological processes of the alluvial system in the Juárez area to USA sites, using Optically Stimulated Luminescence (OSL) dating, and aims to advance understanding of the history of the alluvial fan depositional system of northern México.

There is a globally recognized need to understand the behavior of regional scale alluvial fan systems due to flood risk and sediment transport associated with climate change. Furthermore, understanding the regional effects of climate on alluvial fan deposits is a key research frontier (Owen *et al.,* 2014). However, little previous research has been conducted on Mexican regional alluvial fans. Sparsely inhabited areas of the El Fresnal Playa within the Los Muertos Basin, about 100 km west-southwest of our study area in Chihuahua, have well-exposed sections and allowed Ortega Ramírez *et al.* (2004) to identify three generations of apparent Late Quaternary alluvial fans in the hanging wall and footwall of a major fault. In contrast, the high population density has limited the geologic outcrops in Ciudad Juárez. Although small road cuts are abundant across the fans and expose undisturbed deposit outcrops, these outcrops cannot be easily correlated to build up a clear stratigraphic context for the fan history without geochronological age control. Studies using modern geochronological tools, such as those presented here, are critical towards reaching a strong understanding of alluvial fan dynamics (Owen *et al*., 2014).

One such geochronological tool is OSL dating (Aitken 1998; Rhodes 2011). OSL dating involves measuring electrons that have been displaced by ionizing radiation and in the process became trapped in crystal lattice defects within a mineral (Huntley *et al.*, 1985). The concentration of these electrons increases with time while buried and decreases while in sunlight (Gray and Mahan, 2014). This property has allowed grains of quartz and feldspar to be used as geochronometers for sedimentary units in a variety of geomorphic environments (Rhodes, 2011; Huntley *et al.*, 1985; Wintle and Huntley, 1979; Huntley and Johnson, 1976). Quartz OSL is particularity useful in that the populations of electrons can be easily be removed by sunlight such that there is a high probability of obtaining an accurate age. This is advantageous for alluvial fans where deposition can occur during flash floods which have limited light exposure for sedimentary grains. Additionally, robust statistical techniques, such as the minimum-age-model (MAM), can be used to further control for the uneven light exposure of grains (Galbraith *et al.*, 1999).

In an effort to establish these stratigraphic correlations and obtain age control, we present three new OSL dates on sediment in the alluvial fan system. We use these data to constrain the ages of formation of the fans and discuss the implications of these dates in relation to regional fan processes and Late Quaternary climate. This study will also help improve understanding of the recent geological history of the region in order to place the current problems of flooding in Ciudad Juárez into context. This is part of long-range planning for mitigation of the frequent floods affecting Juárez (Esparza *et al.*, 2007).

2. Rio Bravo and Fans: features and geological setting:

The Pre-Neogene drainage network of the study area was derived during the compressive Laramide orogeny during Paleocene to Eocene time. After that, deformation of Cretaceous rocks created a synclinorium structure and four thrust sheets (oriented NW) were emplaced in the area and formed the rock massif now represented as the Juárez Mountains. Then, during Eocene to Oligocene time, intrusive and extrusive andesite rocks were deposited at the surface. Therefore, many reverse, normal, and oblique faults typical of the basin and range physiographic province were created at this time, in probable response to magmatic events and these faults extend across Chihuahua State, Ciudad Juárez, El Paso (Texas), and New Mexico (Wacker, 1972; Nodeland, 1977; Drewes and Dryer, 1993; Carciumaru and Ortega, 2008; García, 1970). During this time, the ancestral Chihuahua trough was destroyed and its deposits were transported, filling the northern Hueco and Mesilla bolsons, which form typical Basin and Range intermontane basins. Upon this antecedent surface, alluvial fans have been developed, generating the topography upon which Ciudad Juárez is constructed.

The geomorphic evolution is spatially and temporally associated with both tectonic and climatic controls. Down faulted areas produced basins which accumulated the sedimentary Lower, Middle and Upper Santa Fe Formations in the Hueco and Mesilla bolsons (Hawley and Kottlowsky, 1969; Hawley *et al.*, 1976). Furthermore, recent tectonic and/or climatic events associated with the arrival of major ephemeral distributaries of the Rio Bravo during Pleistocene to Holocene time likely produced river terraces. Finally, ages of ash derived from Lava Creek B (of the Yellowstone volcanic), preserved in the highest layer 75 m above the Bravo River floodplain, in the area of University of Texas at El Paso (near Mesa Street), demonstrate incision of the Rio Bravo Channel around 660,000 years ago (660 ka) along the Paso del Norte between the Franklin Mountains and the Sierra de Juárez uplift (Hawley and Kottlowsky, 1969; Hawley *et al.*, 1976).

3. Rio Bravo system evolution during early Pleistocene to Holocene time:

The Río Bravo system and surrounding mountain streams were developed during Plio-Pleistocene to Holocene time (Mack and Seager, 1990; 1995; Mack *et al.*, 2006) leaving a varied regional landscape which can be divided broadly into three major areas (Fig. 1): **A)** The northwest sector composed of the Anapra alluvial fan, where fan processes are actively transporting sediment via ephemeral streams. There is little human modification in this area, with only one major protective structure (the Benito Juárez Dyke) to prevent flooding in the lower reaches of the fan. Otherwise there is no interruption of natural processes. **B)** The central sector comprised of west Snake Stream and east Snake Stream (VAF on Fig. 1), as well as the alluvial fan that is called the Colorado Alluvial fan (CAF) and the piedmont mountain front fan system (PCAF; Fig. 1) and **C)** The southeast sector, which integrates the Palo Chino (PCH) and Jarudo fan system (JAF; Fig. 1). Sectors B) and C) are areas of major construction of buildings and roads.

In the streams, numerous minor dykes trap downstream movement of floodwater and alluvial sediment; and many streams are lined and shaped with concrete and act as both roadways and flood spillways. Therefore in these sectors, the natural fan processes are severely interrupted, and fan action does not operate in its normal mode. However, despite recent human interruptions of fan processes, there is evidence, produced by new dates, that the fan system was also interrupted naturally by dissection and lateral erosion in the Late Pleistocene. The fans were subsequently covered in the lower parts by Rio Bravo sediments, which were later eroded to form terraces, broadly correlating with documented Pleistocene to Holocene climatic processes of New Mexico and El Paso, Texas (Mack and Leeder, 1998). It is worth noting that Mack and Leeder (1998) commented that the Rio Bravo is a special case, because channel migration and avulsion were frequent, and these processes might impact the degree of inter-fingering between the river and alluvial terrace sediments.

Fig. 1 shows a Digital Elevation Model (DEM) of the study area with the distribution of alluvial fans derived from the Juárez Mountains. OSL ages were obtained from the CAF (Fig. 2). At least five shifts of the Rio Bravo tributaries occurred during Pleistocene to Holocene time providing this possible scenario: i) the Lacustrine Cabeza de Vaca Lake of Plio-Pleistocene time (>2.5 Ma) (Strain, 1966; Hawley and Kottlowsky, 1969; Vanderhill, 1986; Gustavson, 1991); ii) the ancestral Rio Bravo path changed again during Middle to Late Pleistocene (0.66 Ma to 0.16 Ma); iii) the older Rio Bravo tributaries built a dissected terrace during Late Pleistocene time (0.16 to 0.10 Ma) (Connell et al., 1998); iv) another terrace system was formed during Late Pleistocene time during 78 to 28 ka (Connell et al., 1998) and again from 15 to 22 ka (Hawley & Kottlowsky 1969; Hawley et al., 1976; Allen and Anderson 1993). During this period of time, younger Rio Bravo tributaries were active again. Finally, v) from 15 ka to the present, the last shift of the Rio Bravo was in progress. Connell and Love (2001) described a series of late Quaternary sands and gravels deposited above the Santa Fe Group (making them Post-Santa Fe Group sediments). These form a series of river terraces adjacent to the modern Rio Grande in New Mexico. Of interest to our study, the upper terraces (informal depositional units Qra and Qay of Connell and Love (2001)) are approximately age-equivalent to the dates we have obtained from the alluvial fans above the city of Juárez (see Connell and Love, 2001, Figs. 3 and 6, noting that Connell and Love did not provide numerical ages).

4. Methods:

Fan distribution was studied and mapped using a combination of field observations and GIS-based topographic mapping, with the caveat that comprehensive fieldwork in the Juárez City area is precluded by the large-scale ground coverage of buildings and roads. Mapping was used to determine the most appropriate locations for OSL sediment sampling (Personious and Mahan, 2000, 2003; Nelson et al., 2015). OSL was applied to samples collected from three specific sites mostly composed of fine Aeolian quartz sands (see Figs. 3A-C). The samples were collected by the first author using the procedure recommended in Cole et al. (2007). Care was taken to keep the samples light-tight during collection and shipment to the OSL laboratory. The samples were processed using protocols set forth in Gray et al. (2015). We used the 250-180 µm because this fraction yielded the largest amount of useable sample. However, even using this larger fraction, we were limited in the number of aliquots available for analysis due to small quartz yields in the lab. Samples were subject to standard HCl, H^2O^2, and HF treatments, magnetic and density separation, and dose rates measured using gamma spectrometry at the U.S. Geological Survey TRIGA facility (Gray et al., 2015).

As noted above, a key problem in fan analysis is that the system has been dissected and extensively covered by the modern development of Juárez City. Determining detailed geometric relationships between the various parts of the fans is effectively impossible. However, it is expected that the uppermost exposed deposits at any site will provide the best opportunity to assemble age data for more recent fan evolution. Consistency of material was achieved by sampling Aeolian sand at all three sites. In each outcrop location, the local stratigraphy shows that the sands sampled for OSL dating are overlain by conglomerates (see Figs. 3A-C); showing episodes of Aeolian deposition are followed by renewed fan building activity. The three sample sites help to constrain the overall general history of the alluvial fans but are specifically tied to the CAF which was selected in order to understand the most recent history of the fan system as the Aeolian layers should be the best candidates for complete bleaching during the depositional processes (see Fig. 2) and also act as proxies for arid or windy periods. Samples are located in the following sites on the CAF:

P1 is located at 13R; 354694.63 m E; UTM 3512048.16 m W; elevation = 1252 m asl
P3 is located at 13R; 355593.59 m E; UTM 3512861.18 m W; elevation = 1201 m asl
P2 is located at 13R; 355730.21 m E; UTM 3512678.11 m W; elevation = 1241 m asl

5. Results:

The OSL data (Table 1) and results (Fig. 4) show the distribution ages for three sites on the CAF. The most notable result from the OSL analyses is that there are two sediment populations in the two younger samples. Furthermore, the older sediment populations can be observed in each of the succeeding samples. Sample P1 shows a population at 31 ka and another population at 45 ka while sample P2 shows a population at 41 ka and a second, older population at 69 ka. This 69 ka population overlaps with the population measured from the oldest samples (P3) at 74 ka.

The results coincide with the period of time covering Oxygen Isotope Stages (OIS) 3 to 5 as follows: Sample P1 is measured at 30 and 45 ka (late OIS Stage 3), Sample P2 is measured at 41 and 69 ka (around the boundary between OIS 4 and 3), and Sample P3 is measured at 74 ka (very latest OIS 5a). These ages represent deposition during both glacial and interglacial phases.

The sample with the tightest equivalent dose distribution was P3 (Table 1). However, P3 was also the oldest sample and came very close to having all quartz OSL trap sites completely filled (usually quartz saturates around 150-200 Grays in traditional OSL measurements; Mahan et al. 2015). The two younger samples were not saturated for two reasons: firstly, because the growth curves (see supplemental) did not exhibit saturation behaviour and secondly because the dose rate was moderate enough (2.80 to 3.26 Gy/ka) to allow natural accumulation to occur for some length of time (Table 1). The quartz in sample P3 was approaching saturation at 208 Grays, so this age could be even older, but is certainly not younger than 74ka (Supplemental). P1 and P2 have two equivalent dose populations with correspondingly higher dispersions, close to or over 30% to 40% (P1 = 29% and P2 = 39%; Table 1).

It is not entirely unexpected to have several populations of grains within poorly sorted alluvial fan sediments (Mahan et al., 2007, 2015; Miller et al., 2010) due to loose sand and gravel packing, fluvial reworking, partial bleaching due to rapid depositional processes, or reactivation of unconsolidated or uncemented sediment layers. However, the Aeolian sediment within the alluvial fan material is most appropriate for OSL dates because the nature of these deposits ensures that maximum exposure to sunlight before deposition occurred (Bateman et al, 2012) and because targeting finer-grained layers within the fan also increases the chances that a majority of the sediments were "zeroed" or bleached before final deposition.

6. Discussion

Relict topography has influenced the alluvial and fluvial history of the study area, producing a complex sedimentary system comprised of river sediments from the Rio Bravo in the northeast, and the alluvial fan material derived from the Juárez Mountains in the southwest. The timing and extent of the inter-fingering of the Rio Bravo terrace sediments with the Juárez Mountains alluvial material is currently unknown and represents an area for future exploration; we will concentrate on evidence provided by the OSL ages and what they indicate about alluvial fan incision and aggradation. Corroborating evidence for substantial, long-term erosion of the fans, using the OSL dates presented in this paper, is shown in Fig. 6, where it can be seen that the fans are incised to a substantial degree, so that the city is built on an eroded fan surface. Furthermore, it is possible that increased Holocene aridity, developed after and throughout the last glacial phase, may have led to substantial degradation of the fans.

6.1 Juárez Alluvial Fan ages

The younger of the two ages of P1 and P2 are more reliable than the older ages of these two samples, and the younger dates are obtained using a Minimum Age Model (MAM) (Galbraith et al., 1999). The MAM thus marks three episodes of Aeolian deposition (at approximately 30 ka, 40 ka and 75 ka) contained within the uppermost (youngest) fan structure. At least three explanations for the deposition and the preservation of the sands are possible: **A**) sediment became available early in the two last glacial maxims, when there was more erosion of the highlands due to increased moisture, so that when arid periods effected in the basin there was a ready supply of sand to be deposited on the fans (Ellwein et al., 2011; Ellwein et al., 2015); **B**) dust or sediment became available because of dune activation or reactivation of the easily deflated playa, river terrace, and lower alluvial fan sediments (Muhs, 2013). It is possible that these periods contain episodes of low effective moisture and high dust accumulation due to drying winds as the glacial phase develops, in which case the formation of the Aeolian sands for P1 and P2 match global climate changes. However, this is a broad interpretation, and it is more likely that there were: **C**) Simply more localized controls operating in this region, such as vegetation and wind shifts (Hall et al., 2008; Cole et al., 2007).

Vegetative cover change was highlighted by Harvey et al. (1999) where attention was drawn to the differences in erosion characteristics of Late Quaternary fans in California, which are influenced by the degree to which they are covered by vegetation. In the Juárez area, throughout the fan system, sparse vegetation is obvious, and it has proved difficult to find outcrops or cores containing pollen, seeds, or other physical evidence that the region was previously well vegetated. Ceballos et al. (2010, Fig. 6) provided maps of Pleistocene vegetation throughout México, and identified xeric scrub as the dominant vegetation in the Juárez study area, indicating poorly developed land cover only minimally sufficient to support a land mammal migration corridor between northern central México and southern central USA. Thus, erosion may be sustained in the highlands of the Juárez Mountains leading to aggrading fan development in the Late Quaternary, with subsequent erosion in more recent times in the lower Juárez Mountains. Furthermore, there are studies of global teleconnections that suggest monsoon rains during the Late Quaternary glaciation and possibly earlier (Muhs, 2013; Miller et al., 2010; Coats et al., 2008) along the Pacific coasts of North America, which would be compatible with shifts between Aeolian and conglomeratic deposits in the Juárez fans.

Unfortunately, because of the urban sprawl of buildings and roads, the history of the fans cannot be fully determined, but one key point emerges: The OSL dates reveal the sand has older ages than expected, and suggest that large parts of the fan system became inactive, with the youngest preserved activity being around 30 ka. The amount of erosion on the fans cannot be totally known, and so it remains possible that the fans could have aggraded in the Holocene, with subsequent erosion. To avoid the problem of younger aggradation and subsequent removal, however, the samples were collected from the highest preserved points where it is not likely to have been easily eroded (Figs. 1, 2 and 6, for visual inspection of the geomorphic relationship between the fans and the surrounding hills).

In more recent times, the alluvial system was partly reactivated in the Anapra Fan. The Anapra Fan is active in the north of the study area and this observation suggests shifting of fan aggradation, while abandoning the older parts (where the city is built). It is reasonable to presume from the geometry and activity of the Anapra fan (Fig. 1) and the continued flooding of the city after heavy rainfall events, that the hydrological system has been intermittently to continually active through the Pleistocene to modern times, but has shifted position, abandoning the older fan system starving it of sediment. The older (OSL dated) fans were likely degraded by more recent erosive activity but this cannot be satisfactorily investigated because of the paucity of outcrops in the city. Although making overall interpretations from only three dates is tenuous, these dates do provide valuable preliminary constraints on the history of the area.

6.2 Comparison with other alluvial fans and climate

Comparison between the three OSL ages and the pattern of the global oxygen isotope curve (Fig. 5) shows that there is not a clear relationship between glacial/interglacial cycles and broad-scale regional sedimentary process in the northern México area. The proximity of the fans to the Juárez Mountains, and the repeated local stratigraphy in the three sample sites, suggests that instead localized climatic changes, perhaps influenced by the steep topography of the mountains and the prevailing winds (Muhs, 2013), were a major control on fan formation. It is possible that cool-season Pacific frontal storms cause river flow, ephemeral lakes, and fan incision, whereas periods of intense warm-season storms cause hillslope erosion and alluvial fan aggradation, as suggested by Miller et al. (2010) and Muhs (2013). Alternatively, the regional topography from the Juárez Mountains, across the Hueco Basin to the Franklin Mountains to the north, created a geographically constrained climatic environment that was locally more influential than the global glacial/interglacial cycles. Support for this suggestion comes from recent work on the Rio Grande terraces in the Albuquerque area of New Mexico (Cole et al., 2007), which shows that there is no clear relationship between terrace age and climate in the Albuquerque area: dates on terraces from a variety of dating methods show scatter throughout OIS-6 to OIS-1, with no firm pattern. Furthermore, compilations of alluvial fan cosmogenic geochronology ages demonstrated no clear pattern with climate (Owen et al., 2014), further challenging the idea that alluvial fans are a climate indicator. Hall and Goble (2012, their Fig. 2) described late Pleistocene palaeosols in New Mexico, and measured two OSL dates (81 ± 6 ka and 91 ± 7 ka) for the Lower Aeolian Sand deposited after the Mescalero paleosol, but before the Berino paleosol (this paleosol is dated as Late OIS Stage 3 to Early OIS Stage 2). Thus the Lower Aeolian Sand represents a dry period between two wetter periods as inferred for the paleosols. This Aeolian sand is older than the Juarez P3 sample at 74.3 ka but the two do overlap within error at 75-79 ka. The Aeolian sand from which P3 was collected is overlain by coarse-grained conglomerates that were presumably deposited by high or rapid water flow indicating a humid phase after aridity. Thus we make a tentative correlation between the oldest age of the three dates on Juarez fans on one hand, and depositional events in New Mexico on the other, reflecting a regional climate feature.

McDonald et al. (2003) described the results of climate shifts between latest Pleistocene to Holocene in the Mojave Desert, California, highlighting the increase in wetness that spurred enhanced erosion and transport of sediment, leading to fan development. They also noted that Aeolian and alluvial sediments in the region were deposited at approximately the same time, indicating widespread climate effects on erosion and sedimentation processes. Dorn (2009, Fig. 24.1) drew attention to larger-scale climatic events in relation to the Late Quaternary. In particular Dansgaard-Oeschger Cycles 11 and 12 from the Greenland ice cores that reflect moisture changes in the northern hemisphere are close in time to the Juárez P2 sample. In contrast to interpretations of aridity discussed above for the 74 ka date in this paper, there is evidence in Greenland of temperature rise (implying increase moisture) in the study of Dansgaard-Oeschger cycles by Landais et al. (2004, see their Fig. 3) at the same time, suggesting therefore that the Juárez fans do respond to regional climate controls.

It remains unclear what the influence of short-term climate events, such as ENSO (El Nino – Southern Oscillation) episodes, is on the deposition of sediments in the Juárez alluvial fans. Magana and Conde (2000) demonstrated a tentative link between ENSO events and winter flooding in southern USA and northwestern México. On the other hand, Pavia et al. (2006) showed finer resolution of identification of wet phases involving both ENSO and Pacific Decadal Oscillations. Thus the Juárez region may have been influenced more by Pacific than by Atlantic Ocean processes, and is an avenue for further investigation, although whether it will be possible to extend such interpretations back into the Pleistocene of the study area or not, remains an open question.

The implications of these results for the alluvial-fluvial system studied here in the Juarez area provide an avenue for future work. Thus the OSL ages reported here may be indicators of climatic fluctuations in northernmost México through the late Quaternary that relate to broader scale climate changes, but so far our dated sediments do not allow a firm correlation with wider scale events, and change into the Holocene. Thus we regard our results as preliminary, but showing great promise, and emphasize the need for further dating work.

7. Conclusions

This study has provided the following outcomes:

1. The first numerical ages of Quaternary alluvial fans in northern México as measured by OSL in three samples are: a) Sample P1: contains a minimum age of 31 ka and a second population at 45

ka; b) Sample P2: a minimum age 41 ka and second population at 69 ka; c) Sample P3 has one dominant population at 74 ka. We consider the younger of the two ages for P1 and P2 to be the more reliable. These ages are within the range of OIS 3 to 5. They demonstrate that fan development in the area, now occupied by the city, either terminated in the late Pleistocene, after which there was apparently an extended period of aridity, or was not preserved when the Río Bravo incised the distal fan layers.

2. The oldest age (74 ka) corresponds to the developing glaciation of OIS Stage 4, but the younger two ages relate broadly to the development of the last glacial. These results imply that aridity is locally to regionally controlled, with limited evidence of a global overprint. However, this interpretation is tentative and further research is necessary. Alluvial fan margins inter-finger with fluvial terrace sediments derived from the Rio Bravo indicating an additional component of fan dissection by the Rio Bravo lateral erosion, presumed to be active during earlier times than our OSL ages, but these are not yet dated.
3. The age of the fans are broadly correlated with sand sheets and alluvial fans of other desert areas of the USA, including the Mojave Desert, and there are preliminary indications of relationships between the Juárez fans and climate change in the region.
4. The fan system has been potentially reactivated to form the Anapra fan in the northern part of the study area, but detail is lacking because incision in the distal fans has been affected by the Rio Bravo eroding the stratigraphy as the river changed course.
5. These preliminary dates provide an avenue of investigation for further dating to ascertain the controls on the alluvial fan and fluvial system.

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Figure captions

Figure 1. Location of Ciudad Juárez, northern México (inset map). Main figure shows Digital Elevation Model, created in Arc-GIS, of the study area. CAF = Colorado Alluvial Fan; AAF = Anapra Alluvial FAN; VAF = Viboras Alluvial Fan; CAF = Colorado Alluvial Fan; PCAF = Piedmont Colorado Alluvial Fan; PCHJAF = Palo Chino and Jarudo Alluvial Fan; HB = Hueco Bolson; MB = Mesilla Bolson; JM = Juárez Mountains; FM = Franklin Mountains; Blue line = Rio Bravo (the border between México and USA).

Figure 2. Upper: photograph looking north, of study area from the hill above Camino Real, showing the Colorado Fan where samples for OSL dating were collected. Lower: Detail of DEM showing positions of OSL samples.

Fig. 3. Photos of the three sample sites demonstrating collection from aeolian sand lenses. **A, B and C** are samples P1, P2 and P3 respectively.

Fig. 4. OSL age plots. A-C: radial plots for samples P1-P3 respectively.

Fig. 5. Oxygen Isotope Curve for the last 100 ka, showing the relationship between OIS stages and the dates of the three samples from Juárez described in this paper.

Fig. 6. Photograph looking across El Paso to Ciudad Juárez; the border lies just beyond the high-rise buildings in the middle of the picture. Note that on the Mexican side, the gridded road system is developed across a largely planated surface of the older parts of the fan system, providing geomorphological evidence for a long period of erosion following the youngest OSL date presented in Figs 5 and 6.

Table 1. OSL data showing age results for all three samples. See text for description and discussion.

Figure 1

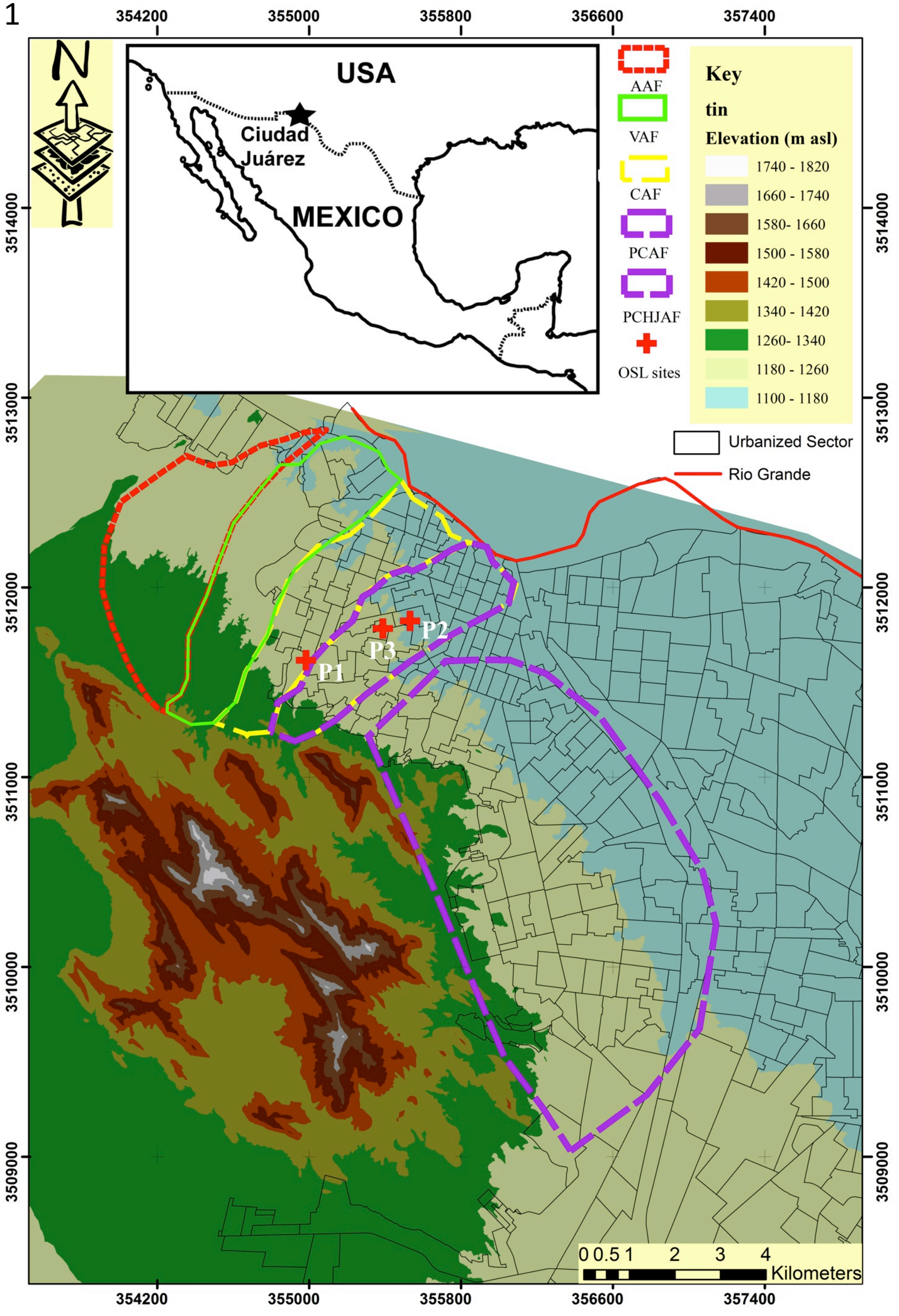

354200
355000
355800
356600
357400
3514000
3513000
3512000
3511000
3510000
3509000
N
USA
Ciudad Juárez
MEXICO
AAF
VAF
CAF
PCAF
PCHJAF
OSL sites
Key
tin
Elevation (m asl)
1740 - 1820
1660 - 1740
1580- 1660
1500 - 1580
1420 - 1500
1340 - 1420
1260- 1340
1180 - 1260
1100 - 1180
Urbanized Sector
Rio Grande
P1
P2
P3
0 0.5 1 2 3 4
Kilometers

Figure 2

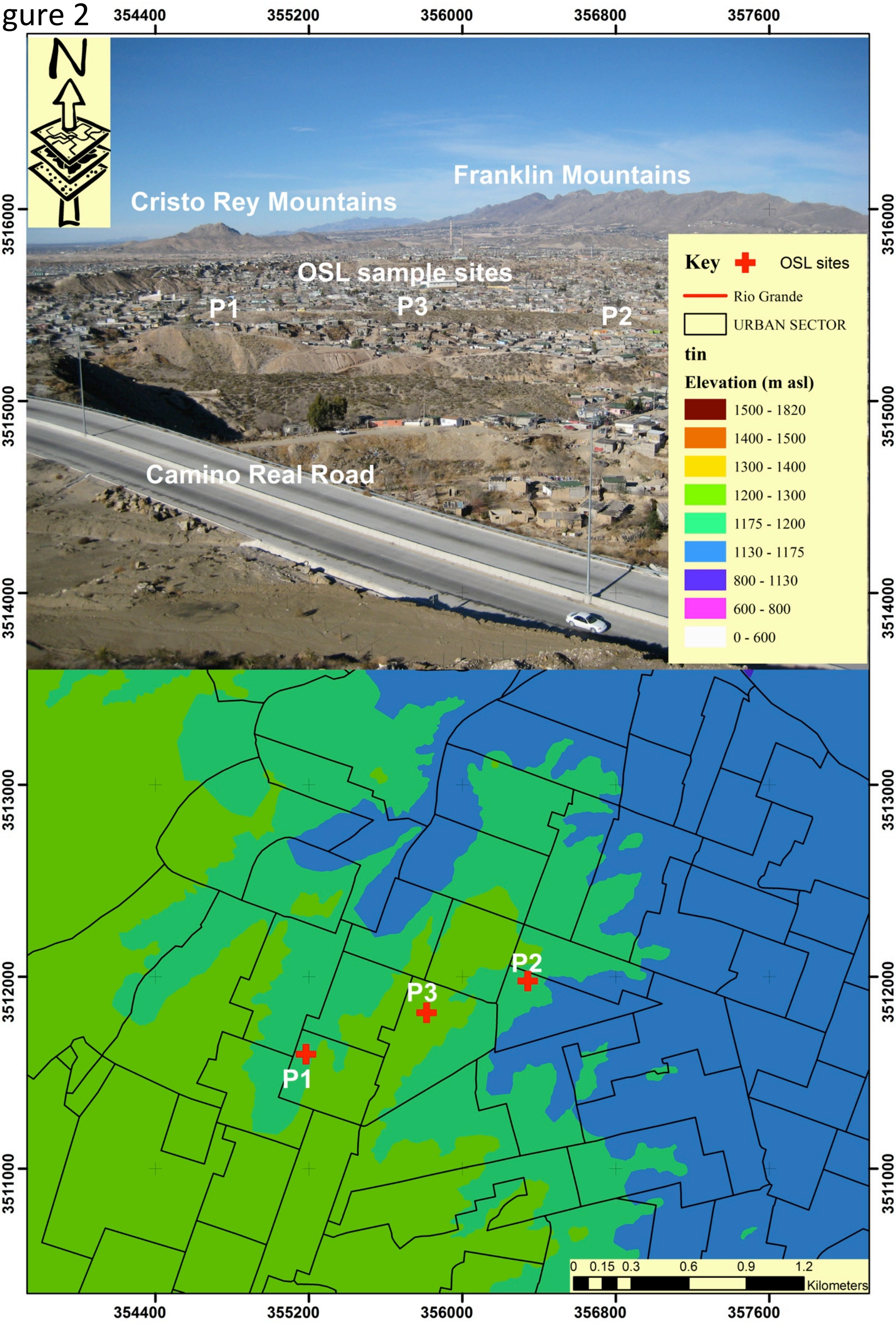

354400
355200
356000
356800
357600
3516000
3515000
3514000
3513000
3512000
3511000
N
Cristo Rey Mountains
Franklin Mountains
OSL sample sites
P1
P3
P2
Camino Real Road
Key
OSL sites
Rio Grande
URBAN SECTOR
tin
Elevation (m asl)
1500 - 1820
1400 - 1500
1300 - 1400
1200 - 1300
1175 - 1200
1130 - 1175
800 - 1130
600 - 800
0 - 600
P2
P3
P1
0 0.15 0.3 0.6 0.9 1.2
Kilometers

Figure 3A

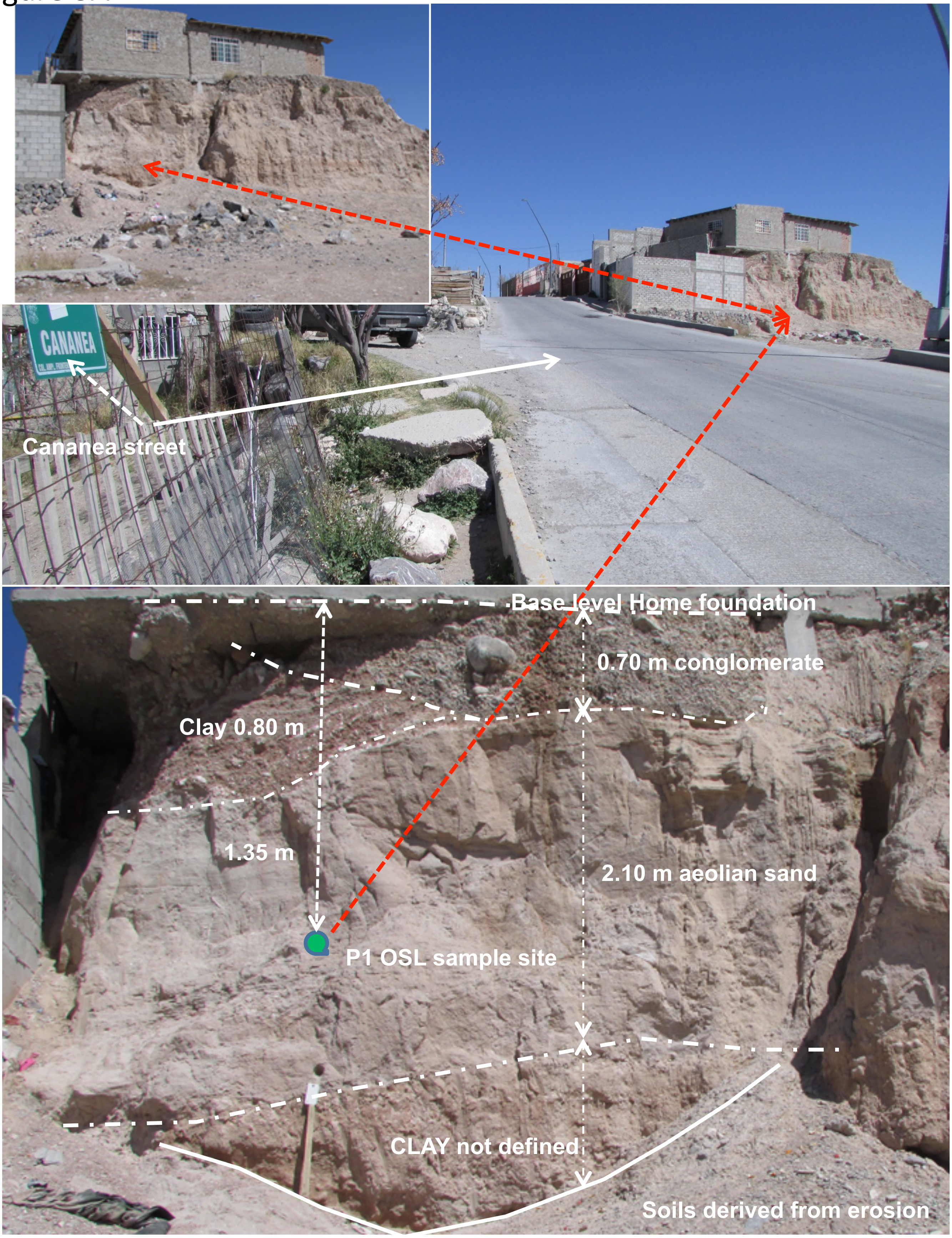
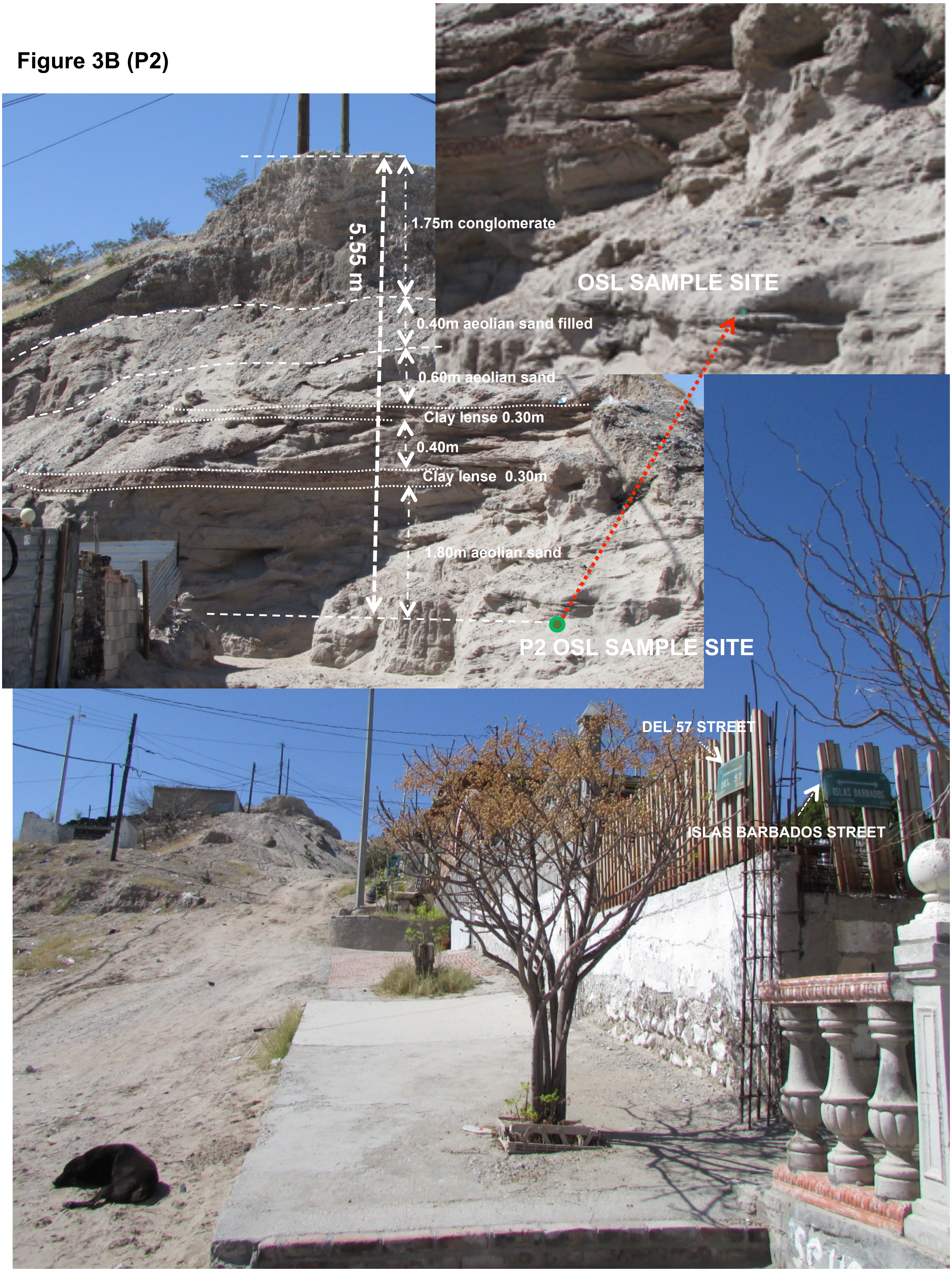


Figure 3A (P1)

Figure 3B (P2)


5.55 m
1.75m conglomerate
OSL SAMPLE SITE
0.40m aeolian sand filled
0.60m aeolian sand
Clay lense 0.30m
0.40m
Clay lense 0.30m
1.80m aeolian sand
P2 OSL SAMPLE SITE
DEL 57 STREET
ISLAS BARBADOS STREET

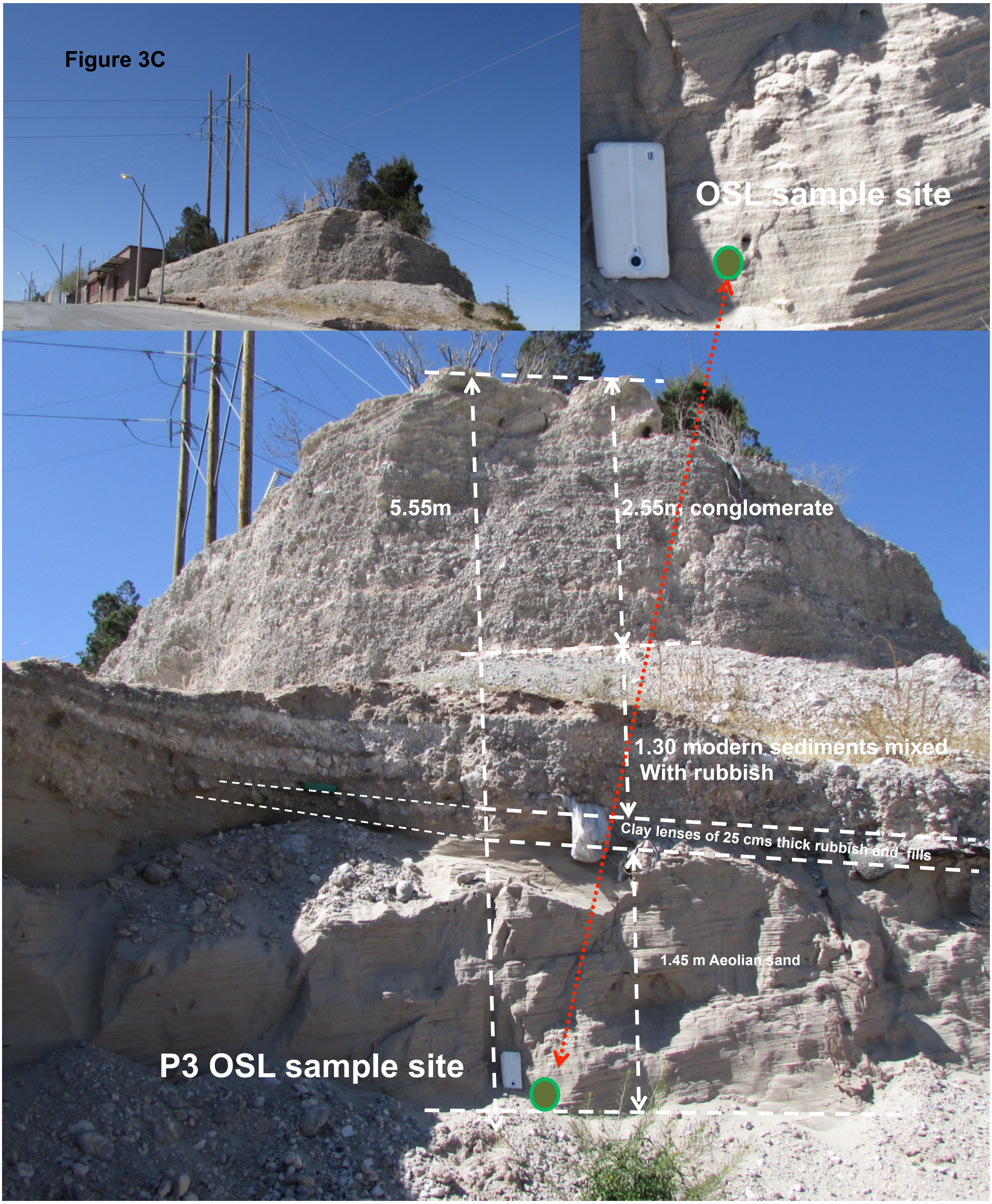
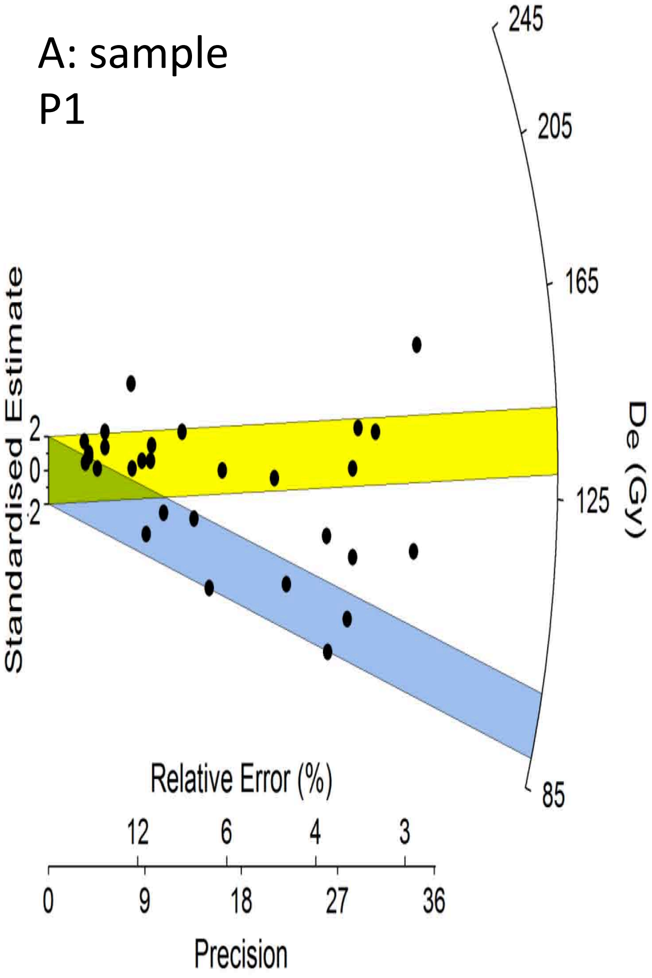
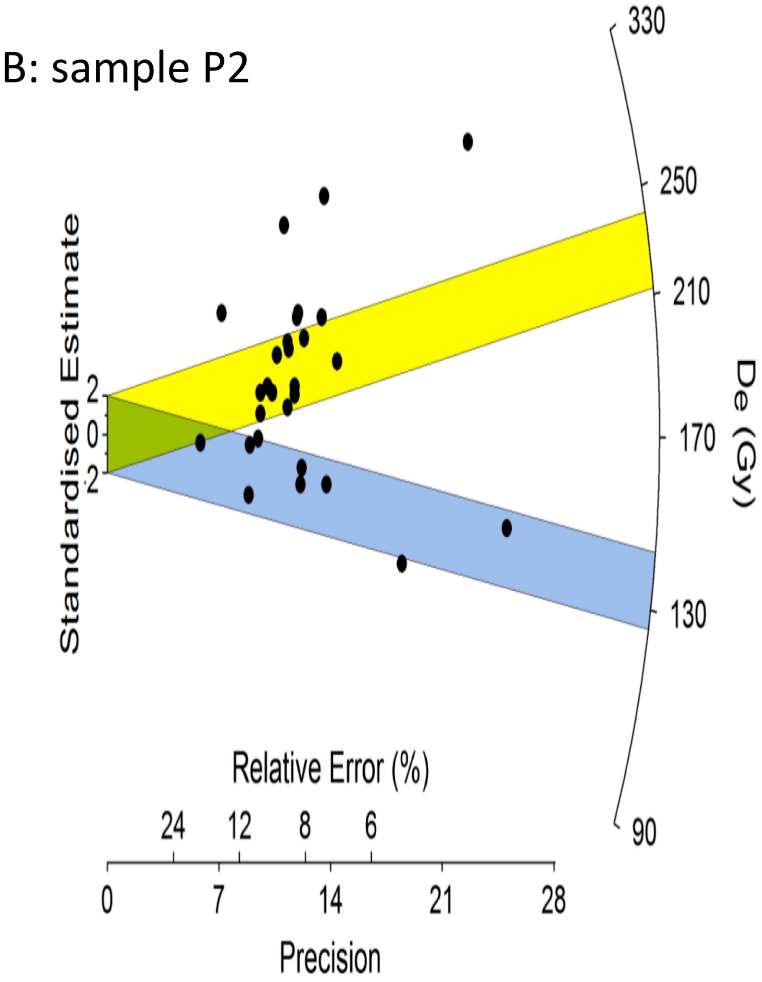


Figure 3C
OSL sample site
5.55m
2.55m conglomerate
1.30 modern sediments mixed
With rubbish
Clay lenses of 25 cms thick rubbish and fills
1.45 m Aeolian sand
P3 OSL sample site

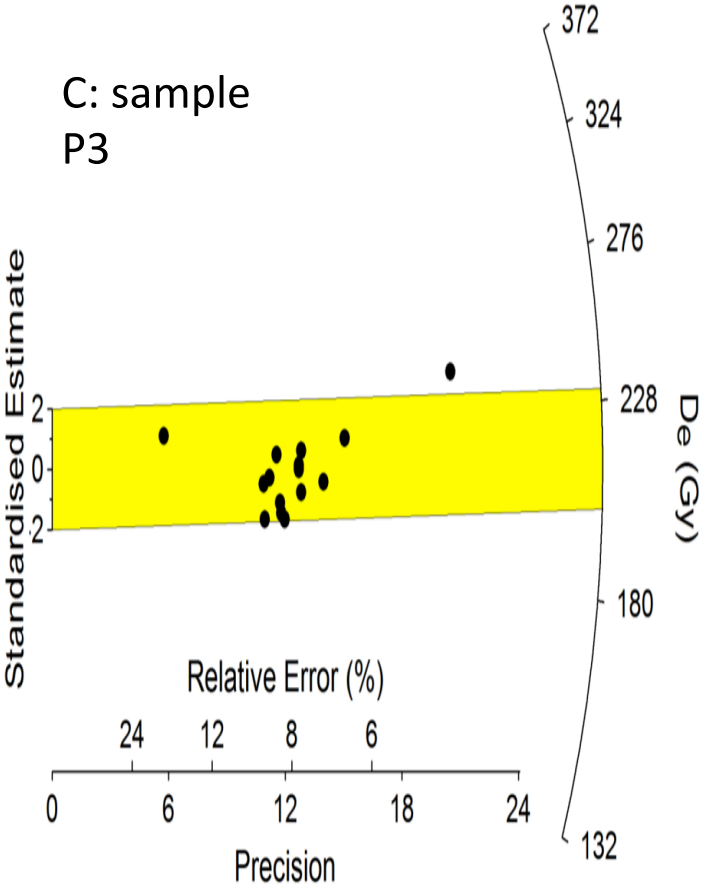
Figure 3C (P3)



A: sample P1



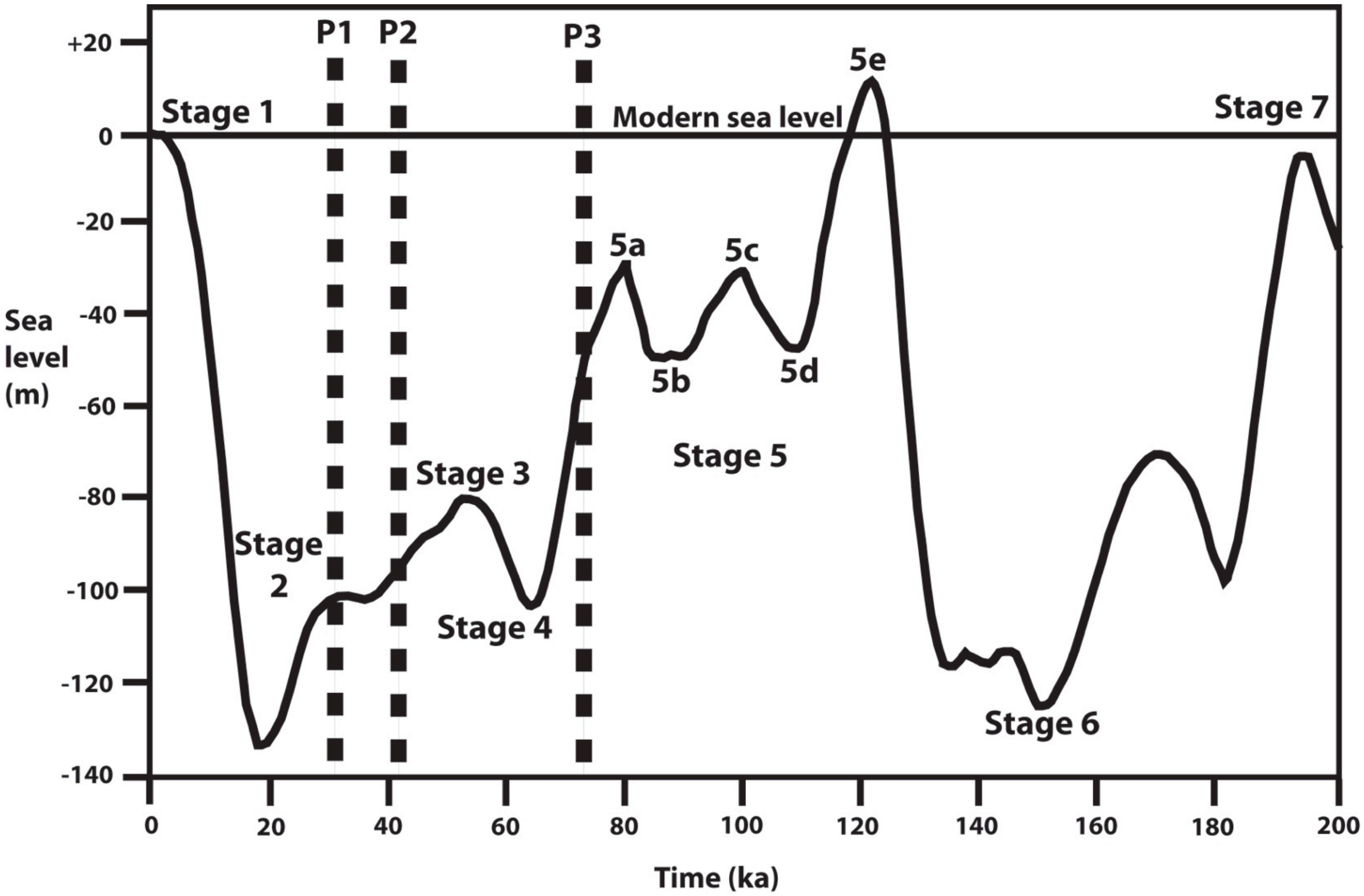
B: sample P2



C: sample P3

Figure 4

Figure 5



P1
P2
P3
+20
0
-20
-40
-60
-80
-100
-120
-140
Sea level (m)
Stage 1
Stage 2
Stage 3
Stage 4
Stage 5
Stage 6
Stage 7
Modern sea level
5a
5b
5c
5d
5e
0
20
40
60
80
100
120
140
160
180
200
Time (ka)

Figure 6

Table 1

Sample ID	% Water Content	K (%)[b]	U (ppm)[b]	Th (ppm)[b]	Total Dose Rate (Gy/ka)[c]	Equivalent Dose (Gys)	N[d]	% Scatter[e]	Age (ka)[f]
P1	1 (32)	2.28 ± 0.03	1.32 ± 0.07	4.25 ± 0.24	3.01 ± 0.10	**93.2 ± 2.26**	**10 (30)**	**29**	**30.9 ± 1.24**
						135 ± 4.54	16 (30)	29	44.9 ± 2.08
P2	1 (32)	2.65 ± 0.07	1.09 ± 0.15	4.97 ± 0.37	3.26 ± 0.13	**134 ± 5.39**	**9 (30)**	**39**	**41.1 ± 2.30**
						225 ± 11.3	14 (30)	39	69.0 ± 4.38
P3	1 (35)	2.24 ± 0.05	0.96 ± 0.11	4.21 ± 0.33	2.80 ± 0.11	208 ± 8.53	15 (15)	10	74.3 ± 4.29

[a] Field moisture, with figures indicating the complete sample saturation %. Ages calculated using approximately 15% of total measured saturation.

[b] Analyses obtained using laboratory gamma spectrometry (high-resolution Ge detector).

[c] Includes cosmic dose rate of 0.23 Gy/ka for P1, 0.13 Gy/ka for P2, and 0.15 Gy/ka for P3 (using methods of Prescott and Hutton, 1994; depth and attentuation)

[d] Number of replicated equivalent dose (De) estimates used to calculate the age. Figures in parentheses indicate total number of measurements included in calculating the represented De and age using the central age model (CAM; bottom age) and the minimum age model (MAM; top age). Preferred ages in bold font.

[e] Defined as “overdispersion” of the D_E values. Obtained by taking std deviation over the average. Values >30% reflect poorly bleached or mixed sediments.

[f] Age for 250-180 microns quartz sand. Exponential fit used on equivalent dose, errors to one sigma.