Soil liquefaction during the Arequipa Mw 8.4, June 23, 2001 earthquake, southern coastal Perú

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Abstract

The Arequipa June 23, 2001, earthquake with a moment magnitude of Mw 8.4 struck southern Perú, northern Chile and western Bolivia. This shallow (29 km deep) interplate event, occurring in the coupled zone of the Nazca subduction next to the southeast of the subducting Nazca ridge, triggered very localized but widely outspread soil liquefaction. Although sand blows and lateral spreading of river banks and road bridge abutments were observed 390 km away from the epicenter in the southeast direction (nearing the town of Tacna, close to the Chile border), liquefaction features were only observed in major river valleys and delta and coastal plains in the meizoseismal area. This was strongly controlled by the aridity along the coastal strip of Southern Perú. From the sand blow distribution along the coastal area, a first relationship of isolated sand blow diameter versus epicentral distance for a single event is ever proposed. The most significant outcome from this liquefaction field reconnaissance is that energy propagation during the main June 23, 2001, event is further supported by the distribution and size of the isolated sand blows in the meizoseismal area. The sand blows are larger to the southeast of the epicenter than its northwestern equivalents. This can be stated in other words as well. The area affected by liquefaction to the northwest is less spread out than to the southeast. Implications of these results in future paleo-liquefaction investigations for earthquake magnitude and epicentral determinations are extremely important. In cases of highly asymmetrical distribution of liquefaction features such as this one, where rupture propagation tends to be mono-directional, it can be reliably determined an epicentral distance (between earthquake and liquefaction evidence) and an earthquake magnitude only if the largest sand blow is found. Therefore, magnitude estimation using this uneven liquefaction occurrence will surely lead to underrating if only the shortest side of the meizoseismal area is unluckily studied, which can eventually be the only part exhibiting liquefaction evidence, depending on the earthquake location and the distribution of liquefaction-prone environments.

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Keywords: Liquefaction; Sand blows; Asymmetric energy distribution; Arequipa 2001 earthquake; Perú
1. Introduction

Southern Perú was hit by a shallow Mw 8.4 (NEIC) earthquake on June 23, 2001. An earthquake of such characteristics is a very likely candidate to have triggered induced effects. This paper discusses the results from a field survey in search of these effects that was initiated 12 days after the Arequipa earthquake, starting in Lima and heading southeast along the coast between Pisco and Tacna (Peruvian border-town with Chile). The survey target was defined based on a preliminary intensity map raised by Instituto Geofísico del Perú (IGP) that clearly placed the damage area southeast of Pisco. This survey was only launched then, only when the road network was partly functioning, although the Pan-American road running along the coast was interrupted several times in occasion of almost all the larger aftershocks during fieldwork. No air reconnaissance was carried out because choppers were attending first priority tasks related to the emergency. The teamwork comprising personnel from IGP and FUNVISIS focused attention on all type of mass wasting and particularly on liquefaction, to whose description this paper is devoted. Special attention was paid to sand blows. No geotechnical investigations, such as SPT or CPT, could be carried out due to logistic limitations and unavailable funding.

In this paper, we have semi-quantitatively evaluated the liquefaction distribution of isolated sand blows triggered by this earthquake, which has showed a very clear trend as we shall discuss herein, in comparison with the seismological data of this Arequipa 2001 event. Strong similarities in the rupture process are revealed by, or deduced from, both – geologic and seismologic – approaches. Finally, the outcome of this evaluation is interpreted in terms of, and is extrapolated to, its application to the past record of earthquake-induced liquefaction and the assessment of past earthquake magnitudes and epicenter locations from liquefaction features.

2. The earthquake and its aftershocks

The Arequipa earthquake struck the Southern Perú coastal region with a moment magnitude (Mw) of 8.4 at 20:33:13 on June 23, 2001. Its epicenter lied at the Peruvian coast at Atico, between Chala and Ocoña (Fig. 1). After IGP, the epicenter coordinates are −16.20° latitude and −73.75° longitude (Tavera, 2002b). Instead, NEIC reports the epicenter at −16.15° latitude and −73.40° longitude, while Harvard CMT solution (energy centroid) places the epicenter at −17.28° latitude and −72.71° longitude (Fig. 1). The main shock took place at the coupled zone of the Nazca subduction under South America (Tavera, 2002c), at a shallow depth of 29 km (Tavera, 2002b). This resulted in extensive damage along the southern Perú (affecting the town of Ocoña, Camaná, Mollendo, Arequipa, Moquegua and Tacna) and northern Chile coasts and as far inland as La Paz – Bolivia – (Tavera, 2002a,b). This inter-plate contact zone is the longest and one of the most active plate boundaries worldwide. The main event was followed in the next 2 weeks by three other rather large earthquakes on June 25 (Mw 6.8; NEIC), July 05 (Mw 6.6; NEIC) and July 07 (Mw 7.5; NEIC); all located east to southeast of the main shock (Tavera, 2002c). Within the first 24 h, a total of 134 ML ≥3.0 aftershocks were recorded, being all located southeast of the June 23 main event (Tavera, 2002b). All these abovementioned seismological aspects clearly point out that the energy directivity and rupture propagation history were SE-directed. In supplement to this, the waveforms, their amplitudes and periods support this and allow estimating that the energy was released towards the southeast (77° 120°S; Tavera, 2002a). Furthermore, the main shock itself comprises three sub-events separated by 5–6 and 36–40 s to the southeast of the first one (Tavera, 2002a). The third and last of these three sub-events composing the main shock lied right below the Camaná region (Tavera, 2002a), which was the hub of the area affected by tsunami waves at least as high as 6 m (Carpio et al., 2002; Jaffé et al., 2003). It is very likely that the whole rupture process (mono-directionality, rupture nucleation, rupture progression) on the coupled zone of the Nazca subduction is highly controlled by the presence of the subducting Nazca ridge at the northwestern tip of the Arequipa 2001 earthquake rupture. The focal mechanism solution of the main earthquake images pure thrust slip along a NNW–SSE striking, 21° E-dipping fault plane (Tavera, 2002c; Fig. 1). This solution depicts well the rather shallow dip (16–20°N) of the subduction slab on the south-
Fig. 1. Map of the southern coast of Peru, showing main rivers, surveyed road and main settlements. Relative location is shown in inset map. It also displays the focal mechanism solutions from IGP for the main event and its main aftershock, as well as the different main earthquake epicenters reported by different agencies. Finally, it also shows the distribution of all reported liquefaction evidence split by type (sand blow, sand dike or lateral spread).
eastern edge of the subducting Nazca ridge; coinciding with where flat subduction in the northwest changes to normal subduction in the southeast (Jordan et al., 1983; Mercier et al., 1992; Gutscher et al., 2000). But the orientation of the fault planes in the focal mechanism solution keeps an angle of some 30\(^\circ\) with respect to the trench orientation (Fig. 1), although they are almost perfectly normal to the GPS-derived convergence vector for the Nazca plate in this region (Kreemer et al., 2003). This excludes any strain partitioning along this portion of the plate boundary.

3. Investigation of liquefaction features in the meizoseismal area

The Southern Perú coast is a very particular landscape worldwide. It is much like a lunar landscape deprived of any vegetation cover due to extreme aridity. It also lacks of soils, but does have some wind-transported sands and volcanic ashes. This arid strip can eventually extend as far inland as a 100 km. Consequently, the search for liquefaction features was narrowed down to very few and localized Holocene sedimentary environments prone to liquefy during strong ground shaking, such as riverbeds and terraces, and alluvial, delta and coastal plains. In fact, very few rivers and streams cross this arid zone and pour into the Pacific. The most important rivers in the study area from northwest to southeast are rare: Acari, Yauca, Ocoña, Camaná, Sihuas, Tambo, Osmore, Locumba and Sama (Fig. 1). These rivers display running water, mostly fed from far upstream into the Andes highlands. Most of these river valleys exhibited both sand blows and venting fractures, related or not to lateral spreading. The two largest delta plains of the Tambo and Camaná Rivers had the most widespread liquefaction distribution (Fig. 1). There is no report of liquefaction in the Ocoña valley by us because the crossing was made at night. It is worth to mention that the field survey was a natural transect along rupture strike because main roads, coast and the subduction trends are all parallel (Fig. 1). In this sense, the reported liquefaction distribution can bring additional insights on the earthquake rupture process, as shown in this case study.

Regardless of the causative process (hydraulic fracturing or associated with lateral spreading), utilized conduits (pre-existing or newly formed cracks, root casts, burrows, rheologic boundaries or any other pre-existing seal weakness) and liquefied feature geometries (aligned or isolated blows, sand dikes), all sand-venting features were investigated, but special attention was paid to isolated sand blows though. This venting feature, when perfectly isolated on the ground, should be the most reliable measure of the pressure exerted by hydraulic fracturing. This in turn must keep a tight relationship with the earthquake ground shaking through the cyclic loading of shear waves when passing through well-saturated, near-surface, cohesionless, granular sediments. In other words, it should be a better gauge of the earthquake energy than all other sand-venting features reported in the literature in the occurrence of moderate-to-large earthquakes. Instead, Obermeier (1996) and Obermeier and Pond (1999) have proposed the use of sand dike width as a tool for characterizing the triggering paleo-earthquake in terms of magnitude and epicentral location. We believe this approach can be of limited applicability since sand dike width can be strongly conditioned by the occurrence of lateral spreading, which in turn is tightly linked to topographic conditions, and not mainly to energy release. Characterization of past topographies over large rough relief areas can be a very difficult task. It may be that this approach is very reliable in areas such as the Mississippi valley – where the approach has been developed – because most topographic irregularities (read free faces or talus) in such a case are introduced by the depth of river incision, which in very flat areas must tend to be rather constant throughout. In that respect, the use of isolated sand blows could have a more general applicability in characterizing past earthquakes. We feel that sand blows – either in the geologic record or on ground surface in association with contemporary earthquakes – can be as easily characterized geometrically as sand dikes, by measuring their base diameter and maximum thickness at the blow mouth instead, although this analysis is only a good semi-quantitative approximation, since both parameters are strongly dependent on several intrinsic factors of the liquefied material. We believe though that the two most conditioning factors among many others are (1) the percent per volume of sand in the
mixture vented to the surface (or the amount of water spouted out, which is proportional to the original water saturation of the liquefied sand layer) and (2) the vented sand grain size. These factors are interconnected. For instance, the larger the grains the more water is contained in the pores, for any specific sorting. These two factors combined control the cone slopes of isolated sand blows when resting on flat ground, as observed by Beltrán and De Santis (1990), and Audemard and De Santis (1991). If the ground surface has some irregularities (e.g., ditches, grooves, scours, furrows) or slope irrespective of how gentle it is inclined, the sand blow circular base is then distorted. In such case, depending on whatever controls the blow shape, either a measure of the minimum diameter must be taken or the shortest and longest base dimensions must be averaged. Other factors intrinsic to the sand spelled out may also exert some control on the blow shape such as grain sorting, roundness and shape. However, very little grain-size analyses have been carried out on spouted sands after individual contemporary earthquakes. At most, some pictures, and occasionally few measures, of sand blows are typically reported in the literature. This is the case of the present study, but this should change in future field reconnaissance surveys if any reliable quantitative analyses are intended. A very rare exception to this is the survey made by Tuttle et al. (2002) after the Bhuj, January 26, 2001, earthquake (Gujarat, India) that gives figures of both diameter and thickness of sand blows. For the Arequipa 2001 earthquake, we have also intuitively focused our attention on the isolated sand blow diameters, as well as on the visual evaluation of grain size of the liquefied sands. Additional factors, not only intrinsic to the liquefiable sands, must actually be taken into account to undertake any robust quantitative analysis – which is not the aim of this rather rough first semi-quantitative approximation – of the geometry of sand blows as a reliable measure of released energy through earthquakes. Depth of water table, as well as depth of liquefaction-prone sand bodies, must be well constrained, which requires specific geotechnical studies and/or instrumentation (piezometer, SPT and CPT, among others). Particular attention must be also devoted to the sealing cap, as to thickness and pre-existing likely weakness zones or features, such as rotten roots, crab burrows, cracks, among several others. In our study, two very strong limitations precluded any quantitative analysis, thus leading us to propose this semi-quantitative approach or hypothesis instead. On one hand, in inaccessible areas such as the coastal strip of Perú, due to rather smooth relief and fairly good road network, running water is only limited to the larger river courses, as mentioned earlier, and superficial water is definitely absent elsewhere (water table can be typically be in excess of 200 m, as pointed out by Wartman et al., 2003), which substantially narrows down areas prone to surface liquefaction, either triggered by earthquake, artesian waters or any other process. This also reduces the number of observational data (refer to Wartman et al., 2003, who reutilized most of the data presented herein). On the other hand, far inland and away from the coastal strip, where water is abundant, liquefaction-prone areas are smaller, narrower and bounded to narrow, sinuous river courses incised in a very steep, inaccessible relief, inside the rough relief of the high Andes (refer to Fig. 3-1 in Wartman et al., 2003). Next, we shall describe all the documented evidence of liquefaction observed from NW to SE, adding further details to the original descriptions from Audemard et al. (2001, 2002) and Gomez et al. (2002). This information was essentially gathered along the South Pan-American road and other minor coastal roads (for survey coverage refer to Fig. 1). First, we shall deal with liquefaction features strictly speaking, and later with occurrence of lateral spreading, which is a combination of gravity-driven lateral translation of almost flat-lying geologic units induced by liquefaction at shallow depth. Reported lateral spreading may have or may not have been accompanied by spouted sands to the surface.

4. Superficial soil liquefaction evidence

As foreseen prior to the field reconnaissance, provided the main event intensity distribution and the extreme aridity of the affected area, the occurrence of liquefaction was only bounded to those few alluvial valleys with permanent running water and active delta plains. This includes the valleys of the Yauca, Ocoña, Camaná, Tambo, Osmore, Locumba and Sama Rivers, from northwest to southeast (Fig. 1). Major relevant
### Table 1: Surface evidence of liquefaction along the coastal strip of southern Peru

<table>
<thead>
<tr>
<th>Locality</th>
<th>Map label (Fig. 1)</th>
<th>Feature description</th>
<th>Sedimentary environment and liquefaction features</th>
<th>Sand grain size</th>
<th>Size of largest sand blow</th>
<th>Depth to water table</th>
<th>Other relevant comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yauca River</td>
<td>1</td>
<td>- Sand boils on small channel bars, in side riverbed</td>
<td>Sand grain size</td>
<td>Very fine to fine</td>
<td>1.50 m in diameter, but typically 0.40 m</td>
<td>Visible and running only 50 cm below sand blow base</td>
<td>First pile of Yauca bridge from the western abutment sunk due to liquefaction in a few tens of centimeters, sagging bridge deck and south banister</td>
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<td></td>
<td>t1.6</td>
<td>- Isolated sand boils with almost circular base on flat ground</td>
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<td></td>
<td>t1.7</td>
<td>- Frequently darker and finer material (mica rich) expelled, probably when water pressure dropped.</td>
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<td></td>
<td>t1.8</td>
<td>- Sand-venting dikes (&lt;1 m long)</td>
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<td></td>
<td>t1.9</td>
<td>- Some sand blows lying on open NE-SW trending ground cracks, paralleling the channel bar edges (lateral spread)</td>
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<tr>
<td>Ocoña River</td>
<td>Not visited</td>
<td>- Widespread liquefaction in the riverbed and its active alluvial and delta plains</td>
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<td>Camana delta</td>
<td>2</td>
<td>- Plentiful light colored liquefied sands resting on pebbly-to-cobbly channel bars, probably supplied by well-oxidized sandy channel bars</td>
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<td></td>
<td>t1.10</td>
<td>- Occasionally, sand-volcano cones aligned along open cracks, individually not longer than 4 m and displaying an en echelon array</td>
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<td></td>
<td>t1.11</td>
<td>- In the coastal plain of the Camana delta, a 30-m-long venting fracture, paralleling both plowing furrows and 5 m away of the river protection embankment, spouted grayish sands in a cornfield, coming from recent anoxic organic-rich delta deposits</td>
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<td></td>
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</tbody>
</table>
| t1.15 | Between Mollendo and Mejía | 4 | Very scarce superficial evidence of liquefaction, except for small isolated sand volcanoes along cracks on top of the present-day sand barrier, at “Urbanización Arizona”.

**Golden Playa Discoteca**

(between Mejía and El Conto) | 5 | Both vent fractures and “apparently” isolated sand boils. Blows aligned on top of almost imperceptible fissures in gravel road carpet, but next to widespread epic bands suggest a provenance from anoxic bodies. Also dark-colored spouting through small cracks—Capping of darker and finer mica-rich fractions at the isolated sand cone mouths (last deposition due to high floatability). |
| t1.16 | Soccer field at La Curva north entrance | 7 | Sand venting along ground cracks, across a soccer field sitting on the Tambo river alluvial plain, due to lateral spreading.

**Tambo riverbed at the El Fraile bridge** | 8 | Numerous rather small (< 0.20 m across), mostly isolated, sand blows on coarse channel bars—Grayish-colored vented sands |
| t1.17 | Osmore delta (Ilo) | 10 | Liquefaction in the Osmore riverbed, near its delta mouth, north of the town of Ilo. Liquefied sands rested on pebbled-to-cobbled channel bars |
| t1.18 | Tambo riverbed at the El Fraile bridge | 8 | Liquefied sands rested on pebbled-to-cobbled channel bars |
| t1.19 | Soccer field at La Curva north entrance | 7 | Sand venting along ground cracks, across a soccer field sitting on the Tambo river alluvial plain, due to lateral spreading.

**Tambo riverbed at the El Fraile bridge** |
| t1.20 | Tambo riverbed at the El Fraile bridge | 8 | Medium, with a significant fraction of gravels at least in the largest blows

**Osmore delta (Ilo)** |
| t1.21 | Osmore delta (Ilo) | 10 | Liquefaction in the Osmore riverbed, near its delta mouth, north of the town of Ilo. Liquefied sands rested on pebbled-to-cobbled channel bars

**Tambo riverbed at the El Fraile bridge** |
| t1.22 | Osmore delta (Ilo) | 10 | Liquefaction in the Osmore riverbed, near its delta mouth, north of the town of Ilo.

**Tambo riverbed at the El Fraile bridge** |
| t1.23 | Osmore delta (Ilo) | 10 | Liquefaction in the Osmore riverbed, near its delta mouth, north of the town of Ilo. Liquefied sands rested on pebbled-to-cobbled channel bars |
| t1.24 | Osmore delta (Ilo) | 10 | Liquefaction in the Osmore riverbed, near its delta mouth, north of the town of Ilo. Liquefied sands rested on pebbled-to-cobbled channel bars |

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</thead>
<tbody>
<tr>
<td>Ilo-La Yarada coast road</td>
<td>11</td>
<td>Near the Locumba River, longitudinal cracks in paddy-field earth dams, suggesting that liquefaction had also happened at depth in this delta plain.</td>
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<td></td>
<td></td>
<td>No evidence of sand spouting</td>
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<td>Very shallow water table</td>
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<tr>
<td>Sama River (Los Baños bridge)</td>
<td>12</td>
<td>Isolated and aligned sand blows, vent fractures and lateral spreads of modest dimensions in the riverbed.</td>
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<td></td>
<td></td>
<td>Sand blows, atop bars in the riverbed, were numerous but not as frequent as in others surveyed rivers.</td>
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<td></td>
<td></td>
<td>Outward grain coarsening of the volcano cones, at least as a capping film, from silts and black micas at the cone mouth to coarse to very coarse sands at the rim.</td>
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<td></td>
<td></td>
<td>Open cracks paralleling channel bar edges. Some of these also trended obliquely but their orientation was controlled by sand extrusion and differential settlement produced by closely located volcanoes.</td>
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<td></td>
<td></td>
<td>Fine to medium</td>
<td>0.50 m in diameter</td>
<td>Shallow water table under features (&lt; 0.50 m deep)</td>
<td>Two large craters at the retaining wall foot of the south bridge abutment, while the earth fill behind it cracked open and settled. Grain-size distribution clearly attests to a progressively dying-out water pressure.</td>
<td></td>
</tr>
</tbody>
</table>
observations as to the liquefaction evidence at the
different localities are summarized in Table 1,
following that same order.

In a general way in this study, we report surface
evidence of liquefaction from the Yauca riverbed (km
598 of the South Pan-American road; station 1 in Fig.
1) to as far southeast as the Sama River, along the
coastal strip of southern Peru, near the Chilean
border. Instead, The Acari River, located only 15
km to the northwest of the Yauca River (station 0 in
Fig. 1), did not exhibit any visible liquefaction
feature, which sharply defines the northern extent
of the area exhibiting surface evidence of liquefac-
tion. Generally speaking, most of the reported
features were lying either inside the few riverbeds
crossed in the study area, atop channel bars (Fig. 2)
or in their alluvial or delta plains. As mentioned
earlier, there is no surface evidence of occurrence of
liquefaction out of these particular sedimentary
environments because the water table is usually too
deep (over a 100 m). Bars in the riverbeds were
typically few tens of centimeters above water level,
and most commonly in the order of 0.50 m, implying
that sand feeders could lie very shallow and were
well saturated. From the sedimentological viewpoint,
the dominant grain-size of liquefied material ranged
between very fine to medium sand (refer to Table 1).

Most sand blows exhibit good grain sorting.

However, the most densely spaced surface expres-
sion of liquefaction has been reported at the delta
plains of the both Camaná and Tambo rivers. For
instance, close to the river mouth of the Camaná
River, in its delta plain, a 30-m-long venting fracture
was seen (Fig. 3). The spouted sand was grayish in
color, implying that the organic content was high,
significantly differing from the vented material
observed in the riverbed which was very light
colored. This also supports that the spouted sand
belonged to the recent anoxic organic-rich delta
deposits of this river. The inundation line of the
tsunami that affected the Camaná region, with run-
ups of as much as 8.2 m high (Jaffe et al., 2003) and
surely above 6 m (Carpio et al., 2002), was very few
tens of meters away, which attests that this evidence
was just very luckily preserved. This line is over 500
m inland from the coast. The parallel orientation of
the venting fracture to that of the embankment
suggests that lateral spreading towards the riverbed
(free face effect) of the river protection embankment,
together with the underlying left riverbank as a unit,
may have played a major role in its formation.

The Tambo delta plain and the adjacent coastal
stretch display the most outspread evidence of
liquefaction of all. This is a straightforward conse-
quence of the size of the liquefaction-prone environ-
ment. The Tambo River delta is the largest of all in

![Fig. 2. Aligned sand volcanoes on very coarse channel bars in the Camaná riverbed, close to its mouth (scale=1m). These bars lie only half a meter above running water.](image-url)
this southern portion of the Perú coast. It extends between Mejía and Corio, for almost 25 km in length along the seashore (see Fig. 1 for relative location). However, Holocene active coastal plains (including sand barriers, mud flats and salt flats) extend as far northwest as south of Mollendo, for an additional strip length of 10 km; totaling a 35-km coastal stretch of Holocene and recent geologic environments of high susceptibility to liquefaction. Besides, the Tambo River alluvial plain stretches inland for some 25 km, between the villages of Punta de Bombón on the coast (near La Curva) and El Fiscal (see Fig. 1 for relative location); the latter being located along the South Pan-American road.

5. Lateral spreading

This phenomenon was the most widespread and common to the visited meizoseismal area of the June 23, 2001, earthquake. It both affected the natural as well as the constructed environment, but road embankments close to irrigation ditches happened to be the most affected feature. It also obeyed the same distribution pattern of superficial evidence of soil liquefaction. However, not all surveyed lateral spreads exhibited evidence of liquefaction on ground surface. It mostly was otherwise. But, few places exhibited the unequivocal evidence proving their concurrent occurrence (Fig. 4). Sand blows or vented sand was sitting on ground fissures or cracks, regardless of their opening width. Next, we shall describe the most relevant localities were this phenomenon was reported.

5.1. Camaná River flood-control earth embankment

The left Camaná River embankment in its delta plain nearing its mouth suffered two strong sagging: (1) where the river showed sandy channel bars in its bed, both embankment shoulders were longitudinally cracked for several tens of meter in length; (2) in a straight section of the river course, the embankment, protected by rock blocks, moved sideward into the river as a rotational slide, inducing top sagging and a semi-circular head scar. On the opposite side, a 1-m-long open crack vented sand and water at the foot of the embankment. Water was still ponded on July 06 and had run off for over 15 m on a very gentle slope. These are supporting evidence that embankment failure resulted from lateral spreading in association with shallow liquefaction. Thickness (height) of the embankment forced water escape to dart such a huge compacted seal. The light color of the vented sand suggests that it came from a well-ventilated sand bed. Therefore, the sand was provided from the riverbed.
but from the floodplains, although the crack and the spouted sand and water were resting on the overbank deposits.

5.2. Coast road between Mollendo and La Curva

Between Mollendo and Mejía, shore-parallel tens-of-meter-long fissures were observed atop of an about 400-m-wide sand barrier near Mollendo. In crop fields on mudflats located behind the abovementioned sand barrier, ground fissures paralleling shallow irrigation ditches were also reported. These are unequivocal evidence of lateral spreading induced by very shallow liquefaction in both conditions, although no venting was reported. In particular, the sand barrier cracking (Fig. 5) should be attributed to sea-front relaxation, while it was induced by lack of lateral confinement by ditches in the cultivated land. In fact, the supporting...

Fig. 4. Aligned sand volcanoes between the edge of a soccer field on the left and the toe of the La Curva–El Arenal road embankment to the right. Spouted water ran toward the viewer (station 7 on Fig. 1).

Fig. 5. Axial crack along the sand barrier, close to Mollendo (station 3 in Fig. 1), due to sea-front relaxation. No surface evidence of liquefaction was found here.
evidence to this was found closer to Mejía, at Urbanización Arizona, where small isolated sand volcanoes were sitting on cracks opened in the sand barrier deposits. The road embankment sitting on the coastal-delta plains of the Tambo River actually happened to be the most damage feature of all by lateral spreading along this road stretch. The embankment, built on the mudflats, was about a 1.5 m high. Dozens of places exhibited longitudinal cracks along the embankment shoulders. Some of these cracks could be of the order of 100 m in length. Few of these cracks could actually cut the asphalt carpet, which had very little vertical displacement. This would imply that the asphalt (acting as a highly cohesion seal) could not be torn apart. When road embankment lateral spreading was more severe, one road lane (half way) could exhibit asphalt carpet cracking. However, road embankment suffered most extensively where road ran parallel to irrigation ditches directly dug in the ground (sector El Boquerón). Lateral spreading was here induced by the void effect of the near ditch, in combination with the liquefaction of shallow saturated cohesionless sands of the Tambo plain. We could only report once that the embankment collapsed along a 100-m-long narrow graben-like feature at the El Boquerón, between El Conto and La Curva (station 6 in Fig. 1). Here, the road embankment was longitudinally trapped between a concrete channel and a ground-dug ditch along both sides (Fig. 6). The embankment spread laterally due to shallow liquefaction, thus compressing the ditch and stretching the opposite shoulder of the embankment (Fig. 6). Local farmers from Boquerón accounted to vertical ejection of a mixture of water and sand in their crop fields during the main earthquake.

Lateral spreading was very well imaged at the water pump station located at the entrance of the Golden Playa Discoteca dirt road, near the Wild Bird Reservation of Mejía (station 5 in Fig. 1). Three small coalescent lateral spreads coevally took place at this “T” road intersection (Fig. 7). The dirt road bridged over a ground-dug few-meter-wide ditch. During the earthquake, two opposite smaller lateral spreads moved sideward into the wide water-full ditch, which in turn triggered a third one that moved away from the main asphalt road. Fig. 7 illustrates this in detail.

5.3. Road along the Tambo River

Between the villages of La Curva and El Arenal, three different road embankment sections underwent sliding normal to the road, in association with lateral spreading. All three failures occurred where the road ran parallel to a shallow irrigation ditch. In all three cases, over half of the asphalt carpet was affected. Nevertheless the most prominent case occurred at the northern entrance of La Curva (station 7 in Fig. 1). It was also the largest of all single lateral spreads reported during this survey. It was as big as a traditional soccer field, measuring some 60 m wide and 100 m long. It actually affected a soccer field almost entirely and the 2-lane-road embankment running along its southeast side. Both the embankment and the soccer field sagged few tens of
centimeters, shared among several sub-parallel arcuate cracks (Figs. 4 and 8). Sagging was produced by differential settlement after water and fine sands were spouted to the surface through a venting fracture and a set of aligned volcano mouths, along the edge of the embankment toe, between the soccer field and road embankment (Fig. 4). Amount of water was that much that ran off for over half the length of the soccer field. The mixture of water and sand was essentially vented by a single fracture, whose cone was 2.5 m long and close to a 1 m wide, in combination with a set of aligned volcanoes stretching over some 8 m (Fig. 4). These features were bordering the soccer field just at the foot of the road embankment, where the latter sank (Fig. 4). This large mass motion on a liquefied layer was set by a small irrigation ditch running along the road embankment, on the opposite side to the soccer field.

However, the most severe damage to road embankments occurred where a shallow irrigation ditch ran...
next to the road, such as between La Curva and El Arenal, between Cocachacra and El Fiscal. Embankment locally cracked and spread laterally due to the free face effect introduced by the shallow irrigation ditch running parallel at the toe of the embankment (similar to image in Fig. 6).

5.4. The Pan-American road along the Osmore valley

Far inland, the road embankment of the South Pan-American road when crossing the Osmore River plain, near Montalvo (south of Moquegua), was longitudinally cracked by outward-directed lateral spreading over tens of meters in length, implying that ground liquefaction occurred beneath the embankment.

6. Discussion

From this field survey observations, the distribution and size of superficial liquefaction evidence show their maximum values at Camaná, progressively diminishing outward both in frequency and in amount of spouted sand and water, both to the northwest and the southeast (Fig. 1). Although no field reconnaissance could be performed upstream along rivers due to logistic limitations, this survey is a perfectly oriented profile along strike of the causative fault (Nazca subducting slab under the South America plate that runs parallel to both the coast and surveyed Pan-American road) of the main earthquake and the aftershock sequence trend. This allows cross-plotting the size of the largest spotted, isolated sand blows with epicentral distance. Arguments on the selection of this liquefaction feature with respect to others have been previously discussed in Section 3. However, some complications in this correlation have arisen because of two different types of uncertainties: one relates to which is the most appropriate epicenter location for the calculation of the epicentral distance; and the other to the reliability that all reported liquefaction features actually were triggered by the main event. The second concern is due to the fact that the Mollendo–Tacna survey was carried out in the same day after the largest (Mw 7.5) “aftershock” that occurred before dawn (4:38 am local time) on July 07, 2001.

Regarding the first aspect, every agency, either national or international, obtains different epicentral solutions for a given earthquake. These differences result from the used seismic datasets and the type of epicenter determination. Since availability of these solutions is very variable, we decided to test the sensibility of this variable (epicentral determination) in the calculations of epicentral distance (between chosen epicenter and reported liquefaction evidence) for three of the published epicenters (Table 2). We selected the IGP, NEIC and Harvard solutions. The USGS epicenter was discarded because it is located between the two extreme solutions from IGP and NEIC, and not substantially varying from those. However, assuming that all reported isolated sand blows were produced by the main event on June 23, 2001, relationships between sand blow diameter and epicentral distance are not qualitatively affected, with respect to either the IGP or NEIC epicenter, but are from the quantitative viewpoint. Regardless of being the epicentral solution provided either by a national (IGP) or an international (NEIC or USGS) agency, the liquefaction evidence spatial distribution for this

<table>
<thead>
<tr>
<th>Locality</th>
<th>Epicentral distance (km)</th>
<th>IGP epicenter</th>
<th>NEIC epicenter</th>
<th>HARVARD CMT epicenter</th>
<th>Sand blow diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acari River</td>
<td>–110</td>
<td>–140</td>
<td>–355</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>Yauca River</td>
<td>–95</td>
<td>–125</td>
<td>–255</td>
<td></td>
<td>1.50</td>
</tr>
<tr>
<td>Camaná delta</td>
<td>120</td>
<td>90</td>
<td>–70</td>
<td></td>
<td>2.00</td>
</tr>
<tr>
<td>Punta Bombón</td>
<td>235</td>
<td>205</td>
<td>100</td>
<td></td>
<td>1.40</td>
</tr>
<tr>
<td>Osmore River (Ilo)</td>
<td>300</td>
<td>270</td>
<td>155</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Sama delta</td>
<td>390</td>
<td>360</td>
<td>255</td>
<td></td>
<td>0.50</td>
</tr>
</tbody>
</table>

The minus (–) sign indicates that the evidence is located to the northwest of the respective epicenter.
particular earthquake is definitely asymmetric in qualitative terms, being the extent of the occurrence of liquefaction always larger to the southeast. It can also be stated that, for a given radius from the selected epicenter, the farther the evidence is, the more pronounced the asymmetry becomes. But when comparing these epicentral solutions with the Harvard epicenter, the latter one is well off the other solutions (Fig. 1) and this is one of the most accessible earthquake catalogue worldwide. This is a significant limitation if this kind of correlation is to be applied and extrapolated to a worldwide dataset, as Castilla and Audemard (under review) have intended. The national seismic catalogues are not typically at hand, except for residents perhaps. Worldwide earthquake data are essentially provided by international agencies such as: NEIC, USGS and Harvard.

Explanation for such a discrepancy between the Harvard and other solutions is given by the rupture history of the main event. Based on how the Harvard epicentral solution is calculated, it is known that it indicates where the largest energy has been released during the earthquake. Conversely, the IGP epicenter, determined from a national array, should provide the earthquake rupture nucleation. As mentioned in Section 3, the isolated sand blow size was the chosen parameter because it should be a better measure of the earthquake energy and duration, regardless of all other parameters (intrinsic and/or extrinsic to the liquefiable sand) that must be taken into account, should the scope of the study be a reliable quantitative analysis. In single-rupture events, we believe that the Harvard and other agency epicentral solutions should be much alike. But in the particular case of the June 23, 2001, earthquake, which comprises three different sub-events, the Harvard solution pinpoints the location of the third and largest sub-event in terms of energy release, which was the largest of the three sub-events after Tavera (2002a). Tavera (2002a) indicates that this third sub-event is lagging almost 40 s behind the first one that should represent the rupture nucleation area. The Harvard epicenter is 160 km southeast of the nucleation (given by IGP epicenter). Then, this raises other doubts: is the liquefaction evidence distribution biased by the rupture process? What epicenter has to be chosen to estimate the farthest liquefaction evidence reported to the southeast: IGP (nucleation and national agency) or Harvard (maximum energy release and international agency) epicenter? Are the farthest evidence to the southeast produced by the first sub-event, the third sub-event or the addition of the three sub-events? As to this, Atkinson et al. (1984) state that seismic shaking duration plays a more prevailing role than just the total energy release. In that sense, we then picked up the IGP solution for this investigation, although is not the most accessible one when a worldwide evaluation is intended. However, we can confidently say that the liquefaction distribution is necessarily influenced by the main-event rupture progression towards the southeast (multi event rupture history), since energy release and shaking duration is progressively added in that direction.

With respect to the second issue, there is neither clear evidence nor suspecting hints of occurrence of several liquefaction episodes triggered by both the main event and any of the largest aftershocks between Mollendo and Tacna, although that region was visited in the hours following the largest (Mw 7.5) aftershock of July 07, 2001, whose epicenter was less than 50 km southeast of Mollendo and close to the visited coast strip (see Fig. 1 for relative location). However, another scientific party during a later reconnaissance photographed liquefaction features at Camaná, resting on the tsunami deposits of the main event, which could only be related to a large aftershock. If these are actually liquefaction features triggered by the largest aftershock, they are 160 km northwest of the aftershock epicenter, but no younger features cutting older ones was actually observed between Mollendo and La Yarada (near Tacna), where should widespread liquefaction have occurred due to closeness to the aftershock epicenter (refer to Fig. 1 for relative location of epicenter with respect to this coastal strip).

Consequently, for plotting the diameter of the largest isolated sand blow of all spotted at each locality versus epicentral distance (Fig. 9), we have assumed that all the reported features were solely triggered by the main event on June 23, 2001 (no evidence supporting otherwise), and that shaking duration is the sum of the three individual sub-event durations composing the main event that nucleated at and propagated southeastward from the IGP epicenter determined from the Peruvian seismologic network data. The number of plotted datapoints of largest sand blows is very few, only six, as a straightforward...
consequence of the very low likelihood of liquefac-

tion potential of the coastal region due to aridity and/
or deeply seated groundwater table. However, this plot shows that isolated sand blow distribution is
definitely highly asymmetrical. Liquefaction is observed much farther to the southeast than to the
northwest (Fig. 9). Fig. 9 does not report all other
isolated sand blows measured during this investiga-
tion, because they clearly lie under the drawn line.
This gun-shot-type distribution below the line does not further support the cross-plot. So, we can
confidently state that the along-subduction-strike
distribution seems not biased significantly by other
parameters proper to the liquefiable sand bodies or
their environment of occurrence, from a semi-quanti-
tative viewpoint. In fact, stream channels in their
downstream section throughout the coastal region are
very similar, as to the liquefaction-prone environ-
ment. In addition, measured sand blows occur atop
channel bars in all cases, which lie less than a meter
above running water, implying that water table was
actually very shallow when liquefaction took place
(refer to Table 1). In the same way, all sand blow
cones used in this relationship are made of medium to
fine grain, light-colored, rather well-sorted sands,
which would suggest that they were fed, environ-
mentally speaking, from similar sand sources (refer to
Table 1). Nonetheless, we cannot confidently state
that all these sand blows have been fed from a similar
range of depth, since no geotechnical investigations
were carried out at the sites exhibiting superficial
liquefaction features.

In addition, this distribution supports that energy
propagation and rupture progression were southeast
directed, as determined from other different evidence
(shape of meizoseismal area based on intensity data,
rupture history derived from seismograms, distribu-
tion of tsunami waves, aftershock distribution,
among others), although epicentral distance to the
farthest liquefaction evidence to the southeast could
be biased by the rupture history, meaning that it
might be actually only 250 km away from the
causative earthquake (third sub-event with high
energetic contribution) instead of 390 km from the
rupture nucleation. Nevertheless, we are convinced
that the very long duration of this large (Mw 8.4)
earthquake resulting from the addition of the three
sub-events, combined with a strong SE directivity
(linked to the rupture history) and a depth of about
30 km, is responsible for such a long epicentral
distance to the farthest liquefaction evidence reported
to the southeast. Eventually, this distance should be
even over 390 km, since sand blows were still 50 cm
across at the Sama River crossing. Instead, they were
not found at a distance of 110 km to the northwest
(station 0 in Fig. 1).
The implications of this finding for paleoseismic assessments relying on paleo-liquefaction features preserved in the recent geologic record, as to earthquake magnitude and epicentral determinations, are of highest significance. For past earthquakes exhibiting highly mono-directional rupture propagation, for which there is no simple way of revealing this aspect from geologic data, an epicentral distance and earthquake magnitude can be reliably estimated only if the largest sand blow is found. This is no easy task because recognition of the spatial distribution of these paleo-liquefaction features is only possible in outcrops, which are never as frequent and thorough as in plan view. Liquefaction associated to the New Madrid 1811–12 sequence is a perfect example of this. Spatial distribution of the larger sand blows induced by that earthquake sequence is still recognizable from aerial photos over a century later (Obermeier et al., 1993; McCalpin, 1996; Obermeier, 1996; Obermeier and Pond, 1999), which eases their search in outcrops. However, shape of areas affected by older liquefaction events in the same region are not so well constrained from paleoseismic investigations (e.g., Munson et al., 1997; Obermeier, 1998; Tuttle et al., 1996; Guccione et al., 2002; Cox et al., 2004). Therefore, those earthquake magnitudes can be hardly estimated with certain reliability, solely based on size of affected area. Consequently, this very frequently implies that pre-historical earthquake magnitudes derived from this type of studies have to be conceived as lower bounds, unless the largest fossil sand blow is hit; unless the size and shape of another liquefaction feature can come in help to constrain it better, such as width and/or frequency of sand dikes as proposed by Obermeier (1996), Munson et al. (1997) and Obermeier and Pond (1999).

Finally, if this type of magnitude assessment – relying on fossil sand blow shape – is to be further developed, a more quantitative analysis needs to be performed on future liquefaction occurrence. In that sense, near-future post-earthquake field surveys will necessarily have to study liquefaction features in a deeper insight. This shall imply that the practice of geotechnical surveys will have to become a must, as well as sampling for grain-size distribution of liquefied sands. The measuring of sand blow shape also needs to become a common practice. This new understanding through data gathering will surely lead to a better application to the past liquefaction record.

7. Conclusions

Although the Arequipa Mw 8.4 June 23, 2001, earthquake triggered widespread liquefaction along the southern coastal strip of Peru, extending eventually over 400 km from the epicenter, sand-venting features and lateral spread were only reported in the major river plains and their deltas, only where there was running water. This fact was conditioned by the extreme aridity of the region and localized extension of the liquefaction-prone environments. Lateral spread resulted to be the most frequent evidence of liquefaction induced by the main event, irrespective of any association with sand spouting or not. If any other event than the main earthquake on June 23, 2001, such as the 7.5 “aftershock” on July 07, 2001, triggered liquefaction, this survey party did not find unequivocal and undisputable evidence of more than one liquefaction event, although part of the survey was carried out in the same day after that largest aftershock. On the contrary, from the sedimentary viewpoint, it could be possible to detect that different feeder beds liquefy during the main event. From the organic content, sand beds from both the overbank sequence and the channel bars spouted sand and water to the surface. Most liquefied sands were very fine to medium grain size but few volcanoes also contained some gravel. In some cases, some outward coarsening could be evidenced in the cone construction, at least during the final stage of water–sand mixture ejection.

The ideal orientation of the surveyed transect paralleling the southern Peru coast allowed to determine from the largest reported sand blow diameter that this earthquake had a strong energy directivity and an asymmetric rupture history directed to the southeast, thus supporting the same finding from several other very different approaches. The implications of this finding are of utmost importance for paleoseismic assessments relying on past liquefaction events preserved in the geologic record of a given region. Due to the limited exposure of past sand volcanoes, the derived magnitude of pre-historic earthquake must be actually considered as a lower
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