Signature of fault zone deformation in near-surface soil visible in shear wave seismic reflections

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[1] Small-throw seismogenic fault segments hidden in the Holocene sediments are crucial but difficult targets in seismic exploration. We report here the detection of the deformation pattern and a concealed fault segment in the unconsolidated sediments at Vila Franca Xira, Portugal, through identification in shear wave reflection data of multiple signatures of ductile deformation associated with faulting. We find step-like changes in the stacking velocity along a shallow subsoil layer boundary, indicating synsedimentary faulting. We also recognize a consistent distortion in the moveout of the reflection events in the raw shear wave data. Synthetic modeling of seismic data helps in interpreting these observations and identifying backscattered energy from a steeply dipping shallow fault zone. Prior to this finding, there was no evidence for Holocene activity of this fault, although the fault is considered to be the most probable source for the disastrous 1531 earthquake. Citation: Ghose, R., J. Carvalho, and A. Loureiro (2013), Signature of fault zone deformation in near-surface soil visible in shear wave seismic reflections, Geophys. Res. Lett., 40, 1074–1078, doi:10.1002/grl.50241.

1. Introduction

[2] Seismogenic fault segments can be present concealed in shallow subsoil. In areas where such faults are anticipated, it is important to know the location and the structure of these faults in order to perform realistic modeling of ground motion, for seismic microzonation studies, to assess the repeat times of past earthquakes, and for characterizing the hydrogeological framework of the subsurface.

[3] Faulting-related deformation in the Holocene soft sediments differs greatly from the brittle deformation in consolidated formations. Unconsolidated and partly consolidated mud generally has porosities between 40% and 80% and may thus undergo strains by loss of pore water alone [Compton, 1985]. Ductile soft-sediment deformations result in grain reorganization, disaggregation bands, intrusion of liquified sand along weak zones, water escape structures, slumping, step-like undulation of a layer boundary due to synsedimentary faulting, mixing of material in the shear zone, and wedge-like penetration of material with a different hydromechanical property [e.g., Neuwirth et al., 2006; van Loon, 2009; Fossen, 2010; Alsop and Marco, 2011].

[4] Two common approaches for investigating faults in shallow subsoil are geophysical exploration and shallow trenching. Trenching and drilling offer directly the ground truth, but being invasive and localized in nature, they cannot be carried out in urbanized or cultivated areas and are done only when the location of a shallow fault is known or strongly anticipated. Among the geophysical methods, high-resolution seismic reflection offers both good resolution and depth penetration. There are numerous earlier studies using P and/or S wave reflections, sometimes together with other geophysical methods and boring or trenching, to investigate shallow fault zones [e.g., Woolery et al., 1993; Benson and Mustoe, 1995; Floyd et al., 2001; Williams et al., 2001; Wang et al., 2004; Sugiwama et al., 2003; Harris, 2009; Campbell et al., 2010]. If the fault throw is significant, causing displacement of several subsurface layers, then that can be seen clearly in surface seismic reflection data. However, in the presence of high background noise in data and/or when the fault displacements are small or the shallow fault zone is steeply dipping, the detection and interpretation are difficult.

[5] At a site in the seismically active Lower Tagus Valley region, Portugal, the presence of small-throw ( < 2 m) active fault segments was suspected in prior studies but could not be resolved and localized. Recently, we have found signatures of faulting-related deformation in seismic shear wave data. This finding highlights not only the possibility of detecting a small-throw fault segment buried in soil through the recognition of multiple pieces of evidence in the seismic wavefield, with essential support provided by numerical modeling, but also, for the first time, the signature of ductile soft-sediment deformation in the shear wave data and the evidence of Holocene activity of this fault. In this letter, we present these findings.

2. Study Area and Prior Investigations

[6] The western part of central Portugal has experienced large earthquakes from time to time. In many occasions, these events migrate to the inland regions, and major faulting occurs at shallow depths within the Quaternary sediments [Rockwell et al., 2009]. These shallow faults, typical of intraplate low-slip-rate regions like the Iberian Peninsula and the Rhine-Graben, have generally steeply dipping fault planes [e.g., Perea et al., 2003; Ferry et al., 2005], and they can produce moderate to large earthquakes causing major damage and loss of lives. These faults are difficult to identify since small scarpers generated by earthquakes are easily erased by surface processes during the long return period.
The study area is located at Vila Franca Xira in the Lower Tagus Cenozoic Basin. It is about 25 km northeast of densely populated metropolitan Lisbon. The area is part of the Ota-Vila Franca de Xira-Lisbon-Sesimbra (OVLS) fault zone [Carvalho et al., 2008]. The Vila Franca Xira fault is thought to be active through the Holocene and to be the source of the disastrous 1531 (MM VIII-IX) Lisbon earthquake which caused over 1000 fatalities [Justo and Salwa, 1998]. However, no direct evidence of faulting has been found so far in the Holocene or Pleistocene sediments. The expression of this fault zone was earlier revealed on oil-industry $P$ wave data, as well as on aeromagnetic and gravimetric data. Following the first localization on the exploration seismic reflection data [Rasmussen et al., 1998; Carvalho et al., 2005], a shallow $P$ wave reflection survey was conducted on the Holocene alluvium sediments by Carvalho et al. in 2006. Of the several fault segments that were interpreted based on seismic and borehole data, two appeared to approach the surface. However, shallow $P$ wave data lacked resolution in the top 40 m, making it impossible to identify any faulting-related feature in the Holocene sediments. The present study is focused in one of those two locations.

From boreholes that were earlier drilled in this area it is known that the top 1.5 m of landfill is underlain by a low-strength muddy sand layer which goes up to 8–10 m depth. From this depth to about 22–25 m, it is silty mud. Beyond that the soil becomes more sandy, finally reaching a clayey sandstone layer below 30 m. At this site, sparse well data and high lateral variability in soil do not allow interpretation of faulting in the shallow Holocene sediments, but at greater depths the evidence of faulting is clear.

3. Shear Wave Reflection Data: Signatures of Fault and Deformation

Shear wave reflection profiling is carried out to image the shallowest part of the OVLS fault zone. Shear waves are more sensitive to subtle changes in the soil type and they offer higher resolution than $P$ waves, especially in water-saturated unconsolidated soils, due to shorter wavelengths. Using a sledge-hammer shear source oriented in the cross-line direction, 96-channel walk-away noise records are collected to optimize the acquisition parameters and ensure no aliasing. In the 2D profiling, 48 horizontal geophones at 0.75 m spacing are used. The source stack count is 4 and the minimum source-receiver offset is 4 m. The inline end-on acquisition geometry has resulted in a constant common midpoint (CMP) fold of 18. Seismic traces are sampled at 2 kHz Nyquist frequency. The location of the profile line is chosen so that it crosses in the middle the previously suspected location of a fault segment approaching the surface. The surface condition is very dry and compacted. This has been helpful in generating relatively high-frequency shear waves and negligible surface (Love) waves. The data processing is restricted to the minimum essential steps to prevent disturbing any effect of shallow faulting in the data. The processing involves geometry installation, vertical stacking, trace editing, gain correction, bandpass filtering, first arrival muting, deconvolution, velocity analysis, static correction, prestack time migration, NMO correction, and CMP stacking.

Constant velocity stacked sections show two prominent reflection horizons at about 200 ms (horizon A) and 420 ms (horizon B) two-way time. These two events are primary reflection events; not only is the stacking velocity higher for event B than for event A, but the attitudes of the two stacked horizons are also very different. Nearby well information and previous seismic refraction velocities suggest that these two horizons correspond to the low-strength sand to silty-mud boundary at 10 m and silty-mud to dense-sand boundary at 22–25 m. Figure 1a shows the migrated time section. The horizons A and B are generally continuous. However, between 31 and 55 m field locations there are disturbances: a change in structure in horizon B and subtle discontinuities in horizon A. Figure 1b shows three representative raw shot gathers.

A time window around the automatically picked peak amplitude at these two horizons is fixed. The semblance
value for the chosen reflection event in each CMP gather is
then estimated for various stacking velocities. The result of
this automatic horizon velocity analysis (HOVA) is shown in
Figure 1c. Deep blue corresponds to the highest semblance
value. Note that, for horizon A (upper panel in Figure 1c),
the maximum semblance velocity changes laterally in a step-
like pattern between field locations 31 and 55 m (lateral
extent indicated by the blue arrow). The stacking velocity
is minimum between 38 and 46 m field locations. For hori-
zon B, corresponding to the older sediment interface, such
variations are not clear. When we change the time window
length in the automatic HOVA, this step-like nature and the
location of the lateral changes in the stacking velocity are
not altered.

[12] The wavelength of the shear wave is about 2.25 m
(with frequency 50 Hz and velocity 100–120 m/s). The
step-like nature of the lateral-velocity change along horizon
A cannot be traced in the time-stacked data. For a two-
way time of 200 ms, a step-like lateral change in velocity
from 100 to 115 m/s corresponds to a change in depth of
1.5 m. Such vertical displacements in a soil-layer interface
resembles the step-like deformation pattern that charac-
terizes earthquake-induced synsedimentary faulting in soft
sediments [Vanneste et al., 1999; Neuwerth et al., 2006].
Such faults develop within the sediment pile during sed-
imentation. Over-pressured under-compacted conditions in
buried mud aid development of these faults [Elliot and
Ladipo, 1981]. Such deformation is realistic for the muddy-
sand to silty-mud boundary at 8–10 m depth in the present
site of investigation. At 49–50 m field location, there is a
clear lateral change in velocity. We find also disturbances
in the stacked image for horizons A and B at this location
(Figure 1a). Because the adjacent CMPs are separated by
only 37.5 cm, the detected step-like changes in the RMS
velocity is indicative of lateral velocity changes in velocity
at or near the interface.

[13] In the search for a supporting evidence, we have
reexamined each raw shot gather along the seismic profile.
We find that between field locations 46 and 52 m, there is a
consistent discontinuity or dent in the moveout of the reflec-
tion events, which can be followed through almost all the
raw shot gathers. In Figure 1b, the red arrows mark this dent.
This feature is not due to any near-receiver disturbances
(notice no change in the direct wave and shallowest reflec-
tions). Note also that this location (46–52 m) coincides with
the location where we detect the sharp lateral change in the
maximum semblance velocity for horizon A (Figure 1c).

4. Shear Wave Reflections: Modeling

[14] Ductile soft-sediment deformation associated with
faulting typically causes fluidization and intrusion of liqui-
fied material locally through weak zones. In Figures 2a
and 2b, a four-layer structure, based on borehole informa-
tion and the general stratigraphy for the Holocene alluvium
in this area [Vis and Kasse, 2009], is shown. Shear wave
velocity has been assigned based on approximate interval
velocity obtained from the stacking velocity. The intrusion
of the liquefied material is simplified by emplacement of
a thin (thickness 1.5 m) vertical structure with shear wave
velocity 10–15% less than the surrounding. This is in agree-
ment with the velocity changes observed in HOVA. At a
seismogenic fault located at a few hundred meters depth,
5. Discussion

Figure 3. Same shot gathers as in Figure 1b, with the backscattered energy marked (blue lines): (a) field data and (b) synthetic data. The red arrow marks a consistent undulation in the reflection moveout. The black arrow in Figure 3b shows the location of the fault segment.

observe in field data, marked by the red arrows in Figure 1b and schematically explained in Figure 2a.

[16] The other important signature of the fault segment in soft sediments, interpreted through synthetic modeling, is the presence of backscattered energy. This is marked by b1–b3 in Figure 2d. A careful look at the raw shot gathers does reveal the presence of these events, with similar orientation to those marked in the synthetic data. It appears that there are more than one fault segment present here. The raw shot gathers shown in Figure 3a are same as those in Figure 1b, but with the interpreted backscattered energy marked by the blue lines. The corresponding synthetic shot gathers are shown in Figure 3b. The location of source and receivers is identical between field and synthetic shot gathers in Figure 3. The presence and location of a dent in the moveout of the reflection event and the presence of backscattered energy from the fault segment resemble between field and synthetic data. The resemblance can be improved by adjusting dip, velocity, and thickness of the fault segment in the model. We find that the backscattered energy arrives from both sides of the fault segment as two discrete events. While the strength of these events increases with an increasing velocity contrast between the fault segment and the surroundings, the separation between them increases with an increase in fault-segment width. The dent in the moveout of the reflection event in shot gather deepens as the velocity contrast and the fault-zone width increase.

6. Conclusions

[19] Through recognition of multiple signatures in the shallow shear wave reflection data, aided by numerical modeling, we have detected faulting-related deformation at a shallow subsoil boundary and interpreted the presence of a shallow buried fault segment. Shear waves offer high resolution in soft soil, and shear wave velocity is sensitive to subtle changes in the soil properties. Shear wave velocity can exhibit the details which may get lost in the stacked seismic section. However, this change can be resolved in the shear wave velocity field, because of the high sensitivity. Through laterally continuous multi-scale analysis of the local velocity-contrast field at a reflection horizon in the shallow subsoil, it has been earlier shown that the fine-scale changes in shear wave velocity along a soil layer-interface contain information about subtle changes in the interfacial nature, which are not recognizable in the stacked data [Ghose and Goudswaard, 2004]. The step-like lateral changes in the RMS velocity that we see along horizon A capture the typical synsedimentary faulting-related deformation pattern. The interpretation of such features, however, requires not only additional evidences but also realistic numerical modeling of seismic wavefield.

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