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Assessment of vulnerability to erosion: digital mapping of a loess cover thickness and stiffness using spectral analysis of seismic surface-waves

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Abstract

Non-invasive geophysical techniques offer an interesting alternative to traditional soil sampling methods, especially for estimating spatial variations of soil parameters in the landscape. The spectral analysis of seismic surface-waves (MASW) can be used to determine the vertical shear-wave velocity (V_s) model (i.e., vertical variations in V_s with depth). In our study, MASW soundings were determined at each point in a grid spread over a wind-eroded field plot of 15600 m². V_s was then mapped in terms of the thickness and stiffness of the superficial loamy material horizon, which are called *ThickLM* and *StiffLM*, respectively. To relate the V_s values to the soil stiffness, cone resistance (Q_d)

24 soundings were also performed using a Dynamic PANDA penetrometer.
25 Concurrently, boreholes were used to sample the same horizon for bulk soil
26 density (ρ_b) measurements. Based on these measurements, large variations in
27 *ThickLM* were observed. The distribution of Vs values along a 130 m transect
28 allowed for the distinction between two layers corresponding to different
29 mechanical properties. The Vs value of 240 m/s was then used as a limit
30 between the loamy material and the underlying clays. This limit was validated
31 using drilling observations performed on the same transect. Therefore, it was
32 possible to map the *ThickLM*, which varied between 0.2 and 6.5 m over the
33 entire field. The comparison between the averaged values of Vs and Qd in the
34 loamy material layer showed a significant correlation ($R^2=0.4$) such that the
35 mapping of *StiffLM* was realised from the Vs map and the Vs-Qd relationship.
36 Density comparison between the ρ_b measured on drill samples and the ρ_b
37 calculated from Vs were also performed using previously published
38 relationships; however, significant correlations were not observed. The obtained
39 maps of *ThickLM* and *StiffLM* were consistent with the expected effects of
40 erosion at the catchment scale and provide indications of historical erosion
41 events. This methodology, which provides a structural and mechanical
42 characterisation of subsurface materials, should help to focus conservation
43 measures to the most threatened areas (i.e., the identification of areas that
44 show a reduced *ThickLM* and increased *StiffLM*, which are associated with high
45 soil erosion vulnerability and/or high compaction state).

46

47 **Keywords**

48

49 Surface wave; Erosion; Digital mapping; Shear wave velocity; Cone resistance

50

51 **1. Introduction**

52

53 The current growing awareness of ecological issues has led to an increasing
54 demand for environmental datasets that are necessary for adequate monitoring
55 and management of various threatened ecosystems. There is also a growing
56 concern regarding the sustainability of biomass production, not only in
57 developing or semi-arid areas (Hadgu et al., 2009; Ye and Van Ranst, 2009) but
58 also in industrialised countries. The increasing demand for cereals and biofuels
59 will further accentuate this trend. Strong relationships between soil erosion, soil
60 depth and soil productivity have been reported in various environments (e.g.,
61 Biot and Lu, 1995; Tendberg et al., 1997; Heckrath et al., 2005; Rejman and
62 Iglik, 2010). The regolith and, more generally, the soil surface material are
63 particularly important, as they support human activities and fulfil numerous
64 ecosystem services (European Commission., 2002-2006). However, our
65 knowledge of the nature and spatial extent of surficial materials is far from
66 complete, and therefore further research is necessary to fill this gap. The ability
67 to accurately and rapidly produce soil depth maps or to delineate areas with

68 limited root penetration depths will, therefore, become crucial to address these
69 issues. Conventional soil surveys are generally based on manual sampling and
70 visual observations of soil pits or auger holes. Such observations are met with
71 both methodological and economic constraints when used for the investigation
72 of large areas. Not only are these observations extremely time consuming – and
73 thus costly – because of the highly repetitive fieldwork that is needed, they can
74 also be destructive to the soil. Moreover, this type of local observation may not
75 represent larger-scale trends in soil properties.

76 Geophysical techniques offer an interesting alternative to traditional soil
77 sampling methods, especially for estimating the spatial variability of physical soil
78 parameters of large areas. These techniques are particularly relevant because
79 most physical soil characteristics are closely related to soil properties (e.g., geo-
80 electrical properties) (Rhoades and van Schilfgaarde, 1976; Robain et al., 1996;
81 Samouëlian et al., 2005). For example, a significant correlation has been
82 demonstrated between the apparent electrical resistivity (ρ) or electrical
83 conductivity (σ) and the soil texture (Williams and Hoey, 1987), soil water
84 content (Kachanoski et al., 1988; Kalinski and Kelly, 1993; Michot et al., 2003),
85 soil salt or nutrient content (Rhoades and Corwin., 1981; Eigenberg et al., 1998)
86 or soil depth (Thompson and Bell., 1996; Chaplot et al., 2001). In contrast to
87 these electrical methods, seismic techniques are not well established in soil
88 sciences but could be particularly promising. Due to the development of
89 subsurface characterisation studies for environmental or geotechnical purposes,

90 the efficiency of seismic methods for estimating ground velocity structures and
91 mechanical properties has seen considerable progress in the recent decades
92 and has been used in various applications in several fields: waste disposal
93 (Lanz et al., 1998), landslides (Grandjean et al., 2007), or hydrogeophysics
94 (Sturtevant et al., 2004). Modern equipment, which generally features 48 or 72
95 recording channels and PC-piloted acquisition software, has made this method
96 user-friendly and has contributed to its popularity. Recently, an adaptation of the
97 sensor line, which is based on unplugged gambled geophones, was proposed
98 to drastically reduce the acquisition times (Grandjean, 2006a; Debeglia et al.,
99 2006). This improvement was supported by the development of new data
100 processing protocols, such as acoustical tomography (Azaria et al., 2003;
101 Grandjean, 2006b) or spectral analysis of surface-waves (SASW) (Nazarian et
102 al., 1983; Park et al., 2000; Grandjean and Bitri, 2006) and related multichannel
103 MASW applications (Foti, 2000; Miller, 1999; Park et al., 1999a, 1999b; Xia et
104 al., 1999), which allowed for the construction of shear waves velocity (V_s)
105 profiles. For example, the analysis of fundamental-mode Rayleigh waves is one
106 of the most common methods for using the dispersive properties of surface
107 waves (Bullen, 1963). This type of analysis provides essential parameters that
108 are commonly used to evaluate near-surface stiffness, which is a critical
109 property for many geotechnical studies (Stokoe et al., 1994). SASW uses the
110 spectral analysis of the ground roll that is generated by an impulsive source and
111 is recorded by a pair of receivers. This method has been widely and effectively

112 used in many geotechnical engineering projects (Stokoe et al., 1994). A single
113 pair of receivers is configured and reconfigured (based on wavelength
114 calculations made during the acquisition) as many times as necessary to
115 sample the desired frequency range. Unfortunately, the necessity of recording
116 repeated shots during multiple field deployments for a given site increases the
117 time and labour requirements relative to a multichannel procedure. Multichannel
118 analysis of surface waves (MASW) is designed to overcome the few
119 weaknesses of the SASW method. The purpose of this study is to test the
120 MASW method as a new tool for characterising soil mechanical properties (i.e.,
121 soil thickness and stiffness) with respect to erosion processes.

122 Instead of sounding the area by systematic drilling, seismic methods were
123 tested to efficiently produce soil property maps. Specifically, we evaluated the
124 feasibility of using mechanical contrasts that exist between the lithologies to
125 map the thickness and stiffness (*ThickLM* and *StiffLM*, respectively) of the
126 surface loamy material horizon using V_s data. Based on this process, we should
127 be able to identify the most threatened areas at the catchment scale, i.e., areas
128 that show a reduced *ThickLM* associated with high *StiffLM*, using V_s data
129 coupled to cone resistance (Qd) data because *StiffLM* can be used as a
130 surrogate for the soil erodibility.

131

132 **2. Materials and methods**

133

134 2. 1. *Description of the study field*

135

136 The study area was located within the Bourville catchment in Normandy, a
137 region of Northern France where erosion that removes the upper soil horizons is
138 a major threat to the main soil functions (i.e., “food and other biomass
139 production, storage, filtering, and transformation of elements among which
140 water and nutrients, biological habitat, and source of raw materials”, European
141 Commission, 2002; Van-Camp et al., 2004). The studied area includes a
142 catchment of the European loess belt in Normandy; this region is severely
143 affected by water and wind erosion with rates often exceeding soil production
144 (between 5 and 10 $\text{ton}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$; Cerdan et al., 2010) (Figure 1). Normandy has
145 a humid-temperate climate with few days of frost. The average temperature
146 ranges between 10 and 12 °C throughout the year, and in August, which is the
147 hottest month of the year, the temperature fluctuates approximately 18 °C. The
148 hilly areas, characterised by a smooth relief (0-7%) and deep superficial layer
149 (>5 m), are used for intensive production of alternating winter and spring crops
150 (e.g., wheat, beets, and maize). An area of approximately 1.5 ha was selected
151 in this catchment to test our approach. Not only was this area highly degraded
152 with a quasi-complete removal of the soil cover in certain areas, its surrounding
153 areas also showed a gradation in the thickness of the loamy material horizon
154 from thick and well conserved in the low elevation locales to thin and eroded in
155 the high elevation areas. The research plot was delineated within the transition

156 zone. This plot, which extended along the steepest slope (Figure 1), shows
157 clear evidence of soil degradation in its north-west and south-east areas with
158 the presence of outcropping clays with flints, both of which are characteristics of
159 on-going loamy material horizon erosion. The entire soil surface was covered by
160 grass vegetation during the field study.

161

162 *2. 2. Geological setting and geomorphologic conditions*

163 The study area was located in north-western France (Normandy), which is
164 characterised by a humid-temperate climate. The topography was relatively
165 smooth with slope gradients ranging between 1% and 4% on the plateau and
166 4% to 10% on valley sides. The area is covered by silt loam soils, which
167 developed on the loess Quaternary deposit, and contains at least 60% silt in the
168 surface horizons. These soils are classified as Neoluvisol in the French
169 Classification system and are described as ‘excessively drained’ according to
170 the USDA (2003) soil drainage classification (Orthic Luvisol, [World Reference](#)
171 [Base, 1998](#)). Such soils are very sensitive to soil sealing because of their low
172 clay content (130 to 170 g.kg⁻¹) and low organic matter content (10 to 20 g.kg⁻¹)
173 relative to more competent underlying clays that are enriched with flints. When
174 in arable use, large areas are left bare and open to rainfall during most of the
175 cultural season, which, combined with the sensitivity to sealing, renders them
176 vulnerable to runoff and water erosion (Figure 2). In contrast, sediments
177 accumulate due to erosion flows in sheltered areas. Based on the

178 geomorphologic conditions, the thickness of the uppermost loamy sediments
179 presents a high variability at the catchment scale.

180

181 *2. 3. Theory and basic principles of the MASW method*

182

183 In the majority of surface seismic surveys, when a compressional wave source
184 is used, more than two-thirds of the total seismic energy generated is imparted
185 into Rayleigh waves (Richart et al., 1970), which is the principal component of
186 surface waves. Assuming vertical velocity variation, each frequency component
187 of a surface wave has a different propagation velocity (called the phase velocity,
188 C_f) at each unique frequency (f) component. This unique characteristic results
189 in a different wavelength (λ_f) for each frequency that is propagated. This
190 property is called dispersion. Although surface waves are considered noise in
191 body-wave surveys (i.e., reflection or refraction profiling), their dispersive
192 properties can be used to infer near-surface elastic properties via Vs evaluation
193 (Nazarian et al., 1983; Stokoe et al., 1994; Park et al., 1998a). The entire
194 process typically used to produce reliable Vs profiles via the spectral analysis of
195 surface waves involves three steps: (1) the acquisition of surface waves (Figure
196 3,5a), (2) the construction of dispersion curves (a plot of phase velocity as a
197 function of f) (Figure 5b), and (3) the back calculation (inversion) of the Vs
198 profile from the calculated dispersion curve (Figure 5c,d). A workflow diagram

199 illustrating the processing method used to obtain reliable Vs profiles with depth
200 is presented in Figure. 4.

201 For step (1), to obtain a good estimation of dispersion curves, we used a multi-
202 station (MASW) configuration, in which receivers are set at several locations
203 and are regularly spaced along a straight line. A seismic source signal was
204 generated via the impact of a hand-held hammer hitting a small iron anvil
205 located on the ground. During the recording, the wavefield was discretised and
206 truncated in both the time and space domain (Figure 5a). The sampling periods
207 in the time domain were $Dt=0.5\text{ ms}$; the numbers of samples was $M=1000$. The
208 near offset (also called origin offset; i.e., the distance between the source point
209 and the first recording point along the line) of $x_0=50\text{ cm}$, the geophone spacing
210 of $Dx=50\text{ cm}$ and the offset range of $L=11.5\text{ m}$ (Figure 3) are the three important
211 acquisition parameters that require proper selection to prevent aliasing, near
212 field, and far field effects (Xia et al., 1999 and Miller et al., 1999). These effects
213 determine the minimum and maximum depth in which Vs can be accurately
214 measured using the MASW method. Due to certain undesirable effects,
215 Rayleigh waves must be studied beyond the near field offset. Far from this
216 distance, they can be considered as horizontally travelling plane waves and
217 processed accordingly. The adaptation of MASW to soil investigations is first
218 conditioned by the possibility of reducing the seismic array (originally consisting
219 of several tens of meters) to approximately several meters, provided that near-
220 field effects are avoided. Second, the frequency range of the seismic signal is

221 increased to obtain a depth of interest up to a maximum of 10 m below the
222 ground surface. Finally, the selected seismic system involved a hammer source
223 that was capable of generating signals in the 1 to few tens of Hz frequency
224 range; and a seismic antenna composed of 24 geophones capable of recording
225 signals from 10 to 200 Hz was used. The entire system was towed behind a
226 vehicle (Figure 3a) to ensure a rapid acquisition. A total of 157 seismic
227 observations were performed along 13 transects with regular 12 m spaces
228 between data points, as shown in Figure 1.

229 For step (2), the generation of a dispersion curve is one of the most critical
230 steps for generating an accurate Vs profile. Dispersion curves are generally
231 displayed as Cf as a function of f (Figure 5b). For impulsive data, a frequency-
232 domain approach (Park et al., 1998b) is used to calculate the dispersion curve.
233 This approach involves a 2D wavefield operation that transforms seismic data
234 from the space-time domain into the Cf - f domain, which is more convenient for
235 highlighting dispersion features.

236 For step (3), the Vs profiles were calculated using an iterative inversion process
237 (Tarantola, 1987) that requires dispersion data (Figure 5c). A least-squares
238 approach allows for the automation of the process (Xia et al., 1999). For the
239 method used here, only the Vs and model thickness are updated after each
240 iteration; Poisson's ratio remains unchanged throughout the inversion. An initial
241 earth model needed to be specified as a starting point for the iterative inversion
242 process. The earth model consists of velocity (P -wave and S -wave velocity),

243 density, and thickness parameters. Among these four parameters, V_s has the
244 most significant effect on the reliable convergence of the algorithm. For each
245 iteration of the inversion process, an update of V_s is calculated, and synthetic
246 dispersion curves are back calculated from this new V_s model. The synthetic
247 dispersion curve is then compared to the observed dispersion curve based on
248 the least-squares method (Figure. 5d). A reliable V_s model is obtained when the
249 misfit between synthetic and observed dispersion curves is minimised. The
250 inversion algorithm used in our study implements all of these aspects and is
251 based on Hermann (1987). The stop criterion for the C_f residuals between
252 synthetic and observed dispersion curves was defined as less than 5 m.s^{-1} .
253 Finally, the interpolation of contiguous V_s models resulting from the inversion
254 process is realised using a natural neighbour method to obtain a 2D V_s section
255 along the transect.

256

257 *2. 4. Penetrometer soundings*

258

259 A dynamic penetrometer with variable energy (Afnor, French norm NF XP P 94-
260 105) can be used to record the mechanical resistance (Qd in MPa) variation
261 with depth (Sanglerat, 1975; Burns and Mayne, 1996) by manually driving a rod
262 into the soil using a standardised hammer. Therefore, a penetrometer can be
263 used to identify variations in soil profiles according to the penetration
264 modulations observed on the rod at each blow of the hammer. Because this

method is easy to use and relatively quick, this portable automatic penetrometer is well adapted for detailed prospecting and mapping (Zhou, 1997). Each penetrometric sounding (CPT) products a vertical cone resistance profile called a penetrogram; the interpretation of the penetrogram allows for the identification of different layers and that estimation of their thickness using two main criteria: well-defined cone resistance thresholds and the shape of the penetrogram. Qd is calculated using the following relationship (Langton, 1999):

272

$$Qd = \frac{1}{A} \times \frac{\frac{1}{2}MV^2}{e} \times \frac{1}{1 + \frac{P}{M}} \quad (1)$$

274

where A is the cone section (2 cm^2), M is the striking mass (kg), V is the impact velocity (ratio between the cell spacing and travel time between cells), P is the struck mass (kg) and e is the drill string progress (m). Qd soundings were performed using a Dynamic PANDA penetrometer (Gourvès and Barjot, 1995) along transect n°5 of the field plot with a regular spacing of 12 m; this survey was conducted at the same location as the collection of seismic data points (Figure 1). In this study, we assimilated the cone mechanical resistance Qd into the soil stiffness.

283

284 2. 5. Drilling observations

285

286 In addition to the abovementioned surveys, 4 drilling observations were
287 performed on the same transect with a spacing of 40 m in the midslope and 20
288 m in the footslope regions (Figure 1). Each borehole was excavated in the
289 north-west to south-east direction to depths of 1.85 m, 3.5 m, 6 m and 1.7 m.
290 Drilling cores were used to estimate *ThickLM* and for laboratory measurements
291 of the water content (θ), the real density of the solid (ρ_r) and the bulk density
292 (i.e., the density of the sample as a whole) (ρ_b) in the loamy layer; these results
293 are shown in Table 1.

294

295 2. 6. Sensitivity of Vs to soil mechanical properties

296

297 Numerical relationships between soil mechanical properties and Vs have
298 been previously published. One of these relationships, which is given by elastic
299 theory and is an essential property for evaluating dynamic responses and the
300 stiffness of soil, is the small-strain shear modulus, G (i.e., a measure of solidity).
301 Values of G are typically determined indirectly by measuring the shear wave
302 velocity, Vs, and the mass density of the soil, ρ , and computing $G = \rho V_s^2$. Other
303 commonly used relationships include the correlation between cone penetration
304 resistance or SPT blow count (N) and Vs and functional forms; this relationship
305 is reported to be $V_s = A \cdot N^B$, where the constants A and B are determined by a
306 statistical regression of a data set. A significant number of correlations have

307 been published for various soil types. Imai and Yoshimura (1975) studied the
308 relationship between seismic velocities and certain index properties for 192
309 samples and developed empirical relationships for all soil types. Sykora and
310 Stokoe (1983) reported that geological age and type of soil are not predictive of
311 V_s , whereas the uncorrected SPT-N value is the most important term. Sykora
312 and Koester (1988) demonstrated a strong statistical correlation between the
313 dynamic shear resistance and standard penetration resistance of soils. Iyisan
314 (1996) examined the influence of the soil type on the correlation between SPT-
315 N and V_s using data collected from an earthquake-prone area in the eastern
316 part of Turkey. The results showed that with the exception of gravels, the
317 correlation equations developed for all soils, sand and clay yield approximately
318 similar V_s values. Jafari et al. (2002) presented a detailed historical review of
319 the statistical correlation between SPT-N and V_s . Hasancebi and Ulusay (2006)
320 studied similar statistical correlations using 97 data pairs collected from an area
321 in the north-western part of Turkey and developed empirical relationships for
322 sands, clays, and all soils irrespective of soil type. Ulugergerli and Uyanik
323 (2007) investigated statistical correlations using 327 samples collected from
324 different areas of Turkey and defined the upper and lower bounds of an
325 empirical relationship instead of a single average curve for estimating seismic
326 velocities and relative densities.

327 These previous studies, as well as a qualitative comparison of data available on
328 our study site, demonstrate the good correlation of V_s to soil mechanical

329 properties and allow for the expectation of a relatively good characterisation of
330 StiffLM using Vs and an accurate estimation of ThickLM (Figure 6) in this
331 context.

332

333 **3. Evaluation of ThickLM and StiffLM of the loamy material horizon**

334

335 *3. 1. Relationships between Vs and CPTs*

336 The distribution of Vs values inverted along the transect n°5 allowed for the
337 discrimination between two populations that corresponded to different
338 mechanical properties. Each population was characterised by Gaussian laws of
339 $\text{mean}_{1\text{st layer}} = 171 \text{ m.s}^{-1}$, $\sigma_{1\text{st layer}} = 80 \text{ m.s}^{-1}$ and of $\text{mean}_{2\text{nd layer}} = 347 \text{ m.s}^{-1}$, $\sigma_{2\text{nd}}$
340 $\text{layer} = 76 \text{ m.s}^{-1}$, where σ is the standard deviation (Figure 7). Moreover, the
341 isovalue of $V_s = 240 \text{ m.s}^{-1}$ was highly consistent with the isovalue $Q_d = 20 \text{ MPa}$,
342 which marks the boundary between a soft superficial unit and a competent
343 underlying formation (Figure 8). This observation was then used for the
344 calibration of a Vs threshold value ($V_{s\text{Lim}} = 240 \text{ m.s}^{-1}$) to characterise a
345 mechanical limit used as a criteria to map ThickLM over the entire field based
346 on the entire seismic dataset. Finally, the mean squared error (MSE) between
347 ThickLM observations and estimations were computed using a validation set of
348 4 drilling points that were positioned to be representative of the observed main
349 variability of ThickLM.

350 To study the stiffness of the loamy material-horizon, we compared V_s and Q_d ,
 351 obtained by CPTs, at a same depth. The two parameters can be interrelated
 352 because they are both influenced by effective level of confining stress, the
 353 anisotropic K_0 -stress state, mineralogy, aging, bonding, and other factors
 354 (Mayne and Rix, 1995; Stuedlein, 2010; Dikmen, 2009). We first applied an
 355 exclusion filter to the V_s data with the condition $V_s < V_{sLim}$ to restrict the
 356 analysis to the loamy layer. Then, we computed the average Q_d values in each
 357 interval of V_s 1D models. Nugget effects on the Q_d data, which occur due to the
 358 punctual presence of various defects (e.g., pebbles) in the medium, were
 359 previously removed from the dataset using an interpolating operator. Figure 9
 360 shows the linear regression between V_s and Q_d where a correlation between
 361 Q_d and e^{V_s} is observed with $R^2=0.4$ and a two-tailed P value less than 0.0001.
 362 By conventional criteria, this difference is considered to be extremely
 363 statistically significant even if samples are highly scattered. Therefore, we
 364 predicted Q_d according to V_s using the following equation:

365

$$366 \quad Q_d = 1.2965e^{0.0057V_s} \quad R^2 = 0.4 \quad P < 0.0001 \quad (2)$$

367

368 Mapping of the spatial variation of *StiffLM* as a function of the average Q_d
 369 calculated over *ThickLM* using Eq. (2) then becomes possible over the entire
 370 field. Density comparisons between the ρ_b measured for the drill samples and
 371 the ρ_b calculated from V_s using published relationships (Mayne, 2001) were

372 also performed, and no significant correlations were determined. This absence
373 of correlations was probably due to the lack of ρ_b values for the clay formation.

374

375 3. 2. *Spatial structure and interpolation of the data*

376

377 The spatial structures of *ThickLM* and *StiffLM* were assessed using variograms
378 that were estimated in four directions at 20°, 55°, 110° and 155° from
379 geographic north. The variograms were generated using all possible sample
380 pairs in a given direction and by grouping these into classes (lags) of
381 approximately equal distance (Matheron, 1965). The variances (one-half of the
382 mean squared difference) of these paired sample measurements were then
383 plotted as a function of the distance between samples to provide a means of
384 quantifying the spatial structure of the data. *ThickLM* and *StiffLM* obtained using
385 *MASW* and Eq. (2), respectively, were then interpolated using ordinary kriging.
386 Ordinary kriging is a geo-statistical method that takes into account both the
387 distance and the degree of variation between known data points and relies on
388 the spatial correlation structure of the data to determine the weighting values.
389 This type of kriging has been shown to provide better performance for soil
390 parameters than other available methods (e.g., Burgess et al., 1981; Myers,
391 1994). The interpolations were accomplished by fitting each of several
392 theoretical variogram models (i.e., linear, Gaussian, spherical, and exponential
393 models) to the empirical isotropic variogram using the least-squares method.

394 The best fit model was then used for the interpolation. Data points were
395 subsequently interpolated to a regular 2×2 m grid using a full second-order
396 polynomial drift function, which is the common practice.

397

398 **4. Results**

399

400 *ThickLM* ranged between 0.2 and 6.5 m with an average of 2.6 m and a median
401 of 2.7 m (Table 2; Figure 10a). As shown by the variogram analysis (Figure
402 11a), *ThickLM* exhibited a moderate anisotropy and spatial structure.
403 Nevertheless, a slight azimuth dependence of less and greater variability was
404 observed at the the 20° and 110° directions, respectively, relative to the other
405 directions of less and greater variability than the other directions. The
406 observations were interpolated over the 120×130 m plot and using an
407 exponential model (sill = 0.75; range = 4.5 m) coupled with a Gaussian model
408 (sill = 9; range = 70 m). The interpolated *ThickLM* map showed a gradual
409 increase in thickness from the north-west limit of the plot, where values were
410 approximately 0.20 m, to the mid-plot position; a gradual decrease was then
411 observed from the mid-plot position to the south-east limit, where *ThickLM* was
412 approximately the same as on the north-west side (Figure 10a). An area of
413 greater *ThickLM* (between 3 and 6.5 m) was observed at the mid-plot position.
414 A local area of greater *ThickLM* (between 1.5 and 3 m) was observed on the
415 north-west side of the plot. The differences between the observed and

416 estimated ThickLM values are shown in Figure 12. The MSE of 0.043 m and
417 $R^2=0.956$ between these two variables over the 4 validation points shows that
418 the estimated ThickLM could be considered to be accurate based on the
419 consideration that the drilling observations are determined to be representative
420 of the overall observed variability of ThickLM over the entire plot.

421 *StiffLM*, which is related to the mean *Qd* calculated over *ThickLM*, ranged
422 between 2 and 6 MPa with an average of 3.78 MPa and a median of 3.68 MPa
423 (Table 2; Figure 10b). As demonstrated by the variogram analysis (Figure 11b),
424 *StiffLM* exhibited a moderate anisotropy and spatial structure. Anisotropy was
425 observed between the 20 and 110° directions with less and greater variability
426 than the other directions. The observations were interpolated over the 120×130
427 m plot using a Gaussian model (nugget = 0.1; sill = 0.7; range = 50 m). The
428 interpolated *StiffLM* map showed a gradual decrease in stiffness from the north-
429 west limit of the plot, where the values range between 5 and 6 MPa, to the mid-
430 plot position; a gradual increase from mid-plot position to the south-east limit,
431 where *StiffLM* presented an lower stiffness than on the north-west side, was
432 also observed (Figure 10b). An area of lower *StiffLM* (between 2 and 4 MPa)
433 was observed at the mid-plot position. A local zone of lower *StiffLM*
434 (approximately 4 MPa) was observed in the north-west side of the plot.

435

436 **5. Discussion**

437

438 The maps of *ThickLM* and *StiffLM* were in good agreement with the expected
439 consequences of the on-going erosion of the loamy material horizon: a
440 gradation in the thickness of the loamy material-horizon from thick and well
441 conserved in the lower parts to thin and eroded in the upper parts, was
442 observed (Figure 10a). The increase of *StiffLM* at the limits of the study plot
443 shows clear evidence of soil degradation in the north-western and south-
444 eastern zones with the presence of bare soils and outcropping clays and flints,
445 which have a mechanical resistance. The local event of greater *ThickLM* and
446 lower *StiffLM* indicated on Figures 10a and 10b with a black dotted line should
447 correspond to a buried former gully that was photographed at this location 2
448 years prior to the study and was caused by strong runoff activity (Figure 10c).
449 This structural and mechanical characterisation of the loamy material horizon
450 should not only help to focus conservation measures in the most threatened
451 areas (i.e., areas that show a reduced *ThickLM* and increased *StiffLM*
452 associated with high soil erosion vulnerability and/or a high compaction state),
453 but will also help identify historical erosion events. The combination of maps of
454 soil stiffness and surficial sediment depths will allow the development and
455 implementation of soil conservation measures to target high-priority areas.
456 Where climatic scenarios are available, these maps can also be used to
457 calculate the potential productivity loss using simulators, such as the
458 SimPLE.ca model (Bremer et al., 2008). This method will also contribute to the
459 broad discussion of reducing the inherent uncertainty in current soil mapping or

460 attribute determinations. Soil maps show that there can be considerable
461 uncertainty in map unit composition with resulting spatial variability in soil
462 properties within map units (Webb and Lillburne, 2005). Actual soil maps define
463 discrete soil classes, which represent the interpolation of only a limited number
464 of modal soil profiles without capturing the full extent of soil variability (Campbell
465 and Edmonds, 1984; Qi and Zhu, 2011). In the study presented here, the non-
466 destructive mapping of continuous soil properties in space will help to improve
467 the data frequency and allow for the derivation of probability distributions to
468 parameterise the fuzzy nature of the geographical objects that comprise the soil
469 maps (Martin-Clouaire et al., 2000).

470

471

472

473 **6. Conclusions**

474

475 The objective of this study was to test and validate a new geophysical technique
476 for mapping soil properties that are related to soil erosion processes. A seismic
477 experiment coupled with penetrometric measurements form the basis of the
478 proposed methodology. The MASW method was efficient for producing Vs
479 models over large areas. When coupled with penetrometric measurements of
480 Qd variations with depth, high-resolution maps of soil thickness and stiffness

481 can be produced, provided that a correlation is found to occur between Vs and
482 Qd.

483 We demonstrated that accurate mapping of variations in the thickness and
484 stiffness of the loamy material horizon can be obtained by integrating
485 information on the relationship between seismic Vs, soil mechanical resistance
486 and drilling observations into the mapping process. An analysis of the
487 correlation between seismic Vs and soil mechanical behaviours provided an
488 effective basis for the accurate delineation of a specific soil attribute. According
489 to the discussion, the analysis of the correlation between the seismic shear
490 wave velocity and the soil bulk density at an interface of strongly contrasted
491 mechanical properties should be studied further.

492 The future of precise mapping of selected soil properties using geophysical
493 seismic techniques is dependent on the understanding of relationships between
494 geophysical signals obtained from this technology and the overall spatial and
495 temporal variability of soil patterns. As the value of the soil resources and
496 associated ecological services receive greater recognition, digital soil mapping
497 based on seismic shear wave velocity can provide spatial data regarding soil
498 degradation that will serve as an essential tool for soil conservation and/or soil
499 rehabilitation.

500

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502

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511

512 **6. References**

513

514 Afnor, Norme française NF XP P 94-105, Essai de pénétration dynamique à
515 énergie variable, Association française de normalisation, 2000.

516 Azaria, A., C. Zelt, A. Levander, 2003. High-resolution seismic mapping at a
517 groundwater contamination site: 3-D travelttime tomography of refraction
518 data, EGS-AGU-EUG Joint Meeting, Nice, France.

519 Biot Y, Lu X.X. 1995. Loss of yield caused by soil erosion on sandy soils in the
520 UK, Soil use and Management 11 (4)157-162.

521 Bremer E., Black M., Townley-Smith L., Malhi SS., Izaurralde RC., Larney FJ.
522 2008. SimPLE.ca: Simulator of productivity loss due to erosion for
523 Canada, Canadian Journal of Soil Sciences 88 (3) 365-376.

- 524 Bullen, K. E., 1963, An introduction to the theory of seismology: Cambridge
525 Univ. Press.
- 526 Burgess, T., Webster, R., McBratney, A., 1981. Optimal interpolation and
527 isarithmic mapping of soil properties. IV. Sampling strategy. J. Soil Sci. 32,
528 643–659.
- 529 Burns, S.E., Mayne, P.W., 1996. Small and high-strain measurements of in-situ
530 soil properties using the seismic cone penetrometers. TRR 1548 Small-
531 Magnitude Measurements in Geotechnical Engineering. National Academy
532 Press, pp. 81-88.
- 533 J.B. Campbell and W.J. Edmonds, 1984. The missing geographic dimension to
534 soil taxonomy. Annals of the Association of American
535 Geographers, 74 (1984), pp. 83–97.
- 536 Cerdan O., G. Govers, Y. Le Bissonnais, K. Van Oost, J. Poesen, N. Saby, A.
537 Gobin, A. Vacca, J. Quinton, K. Auerswald, A. Klik, F.J.P.M. Kwaad, D.
538 Raclet, I. Ionita, J. Rejman, S. Rousseva, T. Muxart, M.J. Roxo, T. Dostal.
539 2010. The rate and spatial distribution of soil erosion in Europe,
540 Geomorphology 122, 167-177.
- 541 Chaplot, V., Walter, C., Curmi, P., Hollier-Larousse, A., 2001. Mapping field-
542 scale hydromorphic horizons using Radio-MT electrical resistivity.
543 Geoderma 102, 61–74.

544 Debeglia N., Bitri A., Thierry P., 2006. Karst investigations using microgravity
 545 and MASW; Application to Orléans, France. *Near Surface Geophysics*, 4,
 546 215-225.

547 Dikmen, U., 2009. Statistical correlations of shear wave velocity and penetration
 548 resistance for soils. *Journal of Geophysics and Engineering*, volume 6,
 549 number 1.

550 Eigenberg, R.A., Korthals, R.L., Neinaber, J.A., 1998. Geophysical
 551 electromagnetic survey methods applied to agricultural waste sites. *J.*
 552 *Environ. Qual.* 27, 215–219.

553 European Commission (2002). *Towards a strategy for soil protection*, COM
 554 (2002) 179 final. Internet: [http://europa.eu.int/comm/environment/](http://europa.eu.int/comm/environment/agriculture/soil_protection.htm)
 555 [agriculture/soil_protection.htm](http://europa.eu.int/comm/environment/agriculture/soil_protection.htm).

556 European Commission. 2006. Thematic Strategy for Soil Protection,
 557 COM(2006)231 final. Internet: [http://eur-lex.europa.eu/LexUriServ/Lex](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0231:FIN:EN:PDF)
 558 [UriServ.do?uri=COM:2006:0231:FIN:EN:PDF](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0231:FIN:EN:PDF)

559 Foti, S., (2000) Multistation Methods for Geotechnical Characterization using
 560 Surface-waves, Dottorato di Ricerca in Ingegneria Geotecnica.

561 Gourvès, R., Barjot, R., 1995. Le pénétromètre dynamique léger Panda.
 562 Comptes rendus, 11ème congrès Européen de Mécanique des Sols et
 563 des Travaux de Fondations, Copenhague, vol. 3, 83-88.

564 Grandjean G. and Bitri A., (2006) 2M-SASW: inversion of local Rayleigh wave
565 dispersion in laterally heterogeneous subsurfaces: application to Super-
566 Sauze landslide (France). *Near Surface Geophysics*, 367-375.

567 Grandjean, G., 2006a. A seismic multi-approach method for characterizing
568 contaminated sites. *J. Applied Geophys.*, 58, 87-98.

569 Grandjean G., 2006b. Imaging subsurface objects by seismic P-wave
570 tomography: numerical and experimental validations. *Near Surface*
571 *Geophysics*, 275-283.

572 Grandjean, G., Malet, J.P., Bitri, A., and Meric O., 2007. Geophysical data
573 fusion by fuzzy logic for imaging mechanical behaviour of mudslides. *Bull.*
574 *Soc. Geol. France*, 177, 2, 133-143.

575 Hadgu KM., Rossing WAH., Kooistra L., van Bruggen AHC. 2009. Spatial
576 variation in biodiversity, soil degradation and productivity in agricultural
577 landscapes in the highlands of Tigray, northern Ethiopia, *Food Security* 1
578 (1) 83-97.

579 Hasancebi, N. and Ulusay, R. (2006). "Empirical correlations between shear
580 wave velocity and penetration resistance for ground shaking assessments,"
581 *Bull Eng Geol Environ*, 66, 203-213.

582 Heckrath G, Djurhuus J, Quine TA, Van Oost K, Govers G, Zhang Y. 2005.
583 Tillage erosion and its effect on soil properties and crop yield in Denmark,
584 *Journal of Environmental Quality* 34 (1) 312-324.

585 Hermann, R.B., 1987. Computer programs in seismology. Saint-Luis University,
586 USA.

587 Imai, T. and Yoshimura, Y. (1975). "The relation of mechanical properties of
588 soils to P and S-wave velocities for ground in Japan," *Technical Note*, OYO
589 Corporation. Iyisan, R. (1996). "Correlations between shear wave velocity
590 and in-situ penetration test results," *Tech. J. Chamber Civil Eng. Turkey*, 7,
591 1187–99 (in Turkish).

592 Jafari, M. K., Shafiee, A. and Ramzkhah, A. (2002). "Dynamic properties of the
593 fine grained soils in south of Tehran," *J. Seismol. Earthq. Eng.*, 4, 25–35.

594 Kachanoski, R.G., Gregorich, E.G., Van Wesenbeeck, J., 1988. Estimating
595 spatial variations of soil water content using noncontacting
596 electromagnetic inductive methods. *Can. J. Soil Sci.* 68, 715–722.

597 Kalinski, R.J., Kelly, W.E., 1993. Estimating water content of soils from electrical
598 resistivity. *Geotech. Test. J.* 16, 323–329.

599 Langton, D. D., 1999. The PANDA lightweight penetrometer for soil
600 investigation and monitoring material compaction, Ground Engineering.

601 Lanz, E., Mauer, H., Green, A.G., 1998. Refraction tomography over a buried
602 waste disposal site. *Geophysics* 63, 1414– 2007-02-21.

603 Lunne, P., Robertson, P. K., and Powell, J. J. M., 1997, Cone penetration
604 testing in geotechnical practice. E and FN SPON.

- 605 [Martin-Clouaire R., Cazemier D.R., Lagacherie P. 2000. Representing and](#)
606 [processing uncertain soil information for mapping soil hydrological](#)
607 [properties Computers and Electronics in Agriculture 29 \(1-2\), 41-57](#)
- 608 Matheron, G., 1965. Les variables régionalisées et leur estimation: une
609 application de la théorie de fonctions aléatoires aux sciences de la nature.
610 Masson et Cie, Paris. 306 pp.
- 611 Mayne, P.W., 2001, Stress-strain-strength-flow parameters from enhanced in-
612 situ tests, *Proceedings of the International Conference on In-Situ*
613 *Measurement of Soil Properties and Case Histories, Bali, pp. 27-48.*
- 614 Mayne, P. W., Rix, G. J., Correlations between shear wave velocity and cone tip
615 resistance in natural clays, *Soil and Foundations* 35 (1995) (2), pp. 107–
616 110.
- 617 McMechan G. A., Yedlin M. J., 1981, Analysis of dispersive waves by wave field
618 transformation. *Geophysics* vol. 46 p. 869-874.
- 619 Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D., Tabbagh, A.,
620 2003. Spatial and temporal monitoring of soil water content with an
621 irrigated corn crop cover using electrical resistivity tomography. *Water*
622 *Resour. Res.* 39, 11–38.
- 623 Miller, R.D., Xia, J., Park, C.B., and Ivanov, J.M., 1999, Multichannel analysis of
624 surface waves to map bedrock: *The Leading Edge*, 18, 1392–1396.
- 625 Myers, D.E., 1994. Spatial interpolation: an overview. *Geoderma* 62, 17–28.

626 Nazarian, S., Stokoe, K. H., II, and Hudson, W. R., 1983, Use of spectral analysis
 627 of surface waves method for determination of moduli and thicknesses of
 628 pavement systems: *Transport. Res. Record*, **930**, 38–45.

629 Papy F, Douyer C. 1991. Influence des états de surface du territoire agricole sur
 630 le déclenchement des inondations catastrophiques. *Agronomie* **11**: 201–215.

631 Park, C.B., Miller, R.D., Xia, J., Ivanov, J., 2000. Multichannel seismic surface-
 632 wave methods for geotechnical applications. *Proc. of the First Int. Conf. on*
 633 *the App. of Geophys. Methodologies to Transportation Facilities and*
 634 *Infrastructure*, St. Louis, December 11–15.

635 Park, C.B., Miller, R.D., and Xia, J., 1999a, Multimodal analysis of high
 636 frequency surface waves: *Proceedings of the symposium on the*
 637 *application of geophysics to engineering and environmental problems '99*,
 638 115–121.

639 Park, C.B., Miller, R.D., and Xia, J., 1999b, Multichannel analysis of surface
 640 waves: *Geophysics*, 64, 800–808.

641 Park, C. B., Xia, J., and Miller, R. D., 1998a, Ground roll as a tool to image
 642 near-surface anomaly: 68th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded
 643 Abstracts, 874–877.

644 Park, C. B., Xia, J., and Miller, R. D., 1998b, Imaging dispersion curves of
 645 surface waves on multichannel record: 68th Ann. Internat. Mtg., Soc. Expl.
 646 Geophys., Expanded Abstracts, 1377–1380.

- 647 [Qi F., Zhu A-X. 2011. Comparing three methods for modeling the uncertainty in](#)
 648 [knowledge discovery from area-class soil maps Computers &](#)
 649 [Geosciences 37 \(9\), 1425-1436](#)
- 650 Rejman J., I. Iglík. 2010. Topsoil reduction and cereal Yields on loess soils of
 651 Southeast Poland Land Degrad. Develop. 21: 401–405.
- 652 Richart, F. E., Hall, J. R., and Woods, R. D., 1970, Vibrations of soils and
 653 foundations: Prentice-Hall, Inc.
- 654 Rhoades, J.D., Corwin, D.L., 1981. Determining soil electrical conductivity-
 655 depth relations using inductive electromagnetic soil conductivity meter.
 656 Soil Sci. Soc. Am. J. 45, 255–260.
- 657 Rhoades, J.D., van Schilfgaarde, J., 1976. An electrical conductivity probe for
 658 determining soil salinity. Soil Sci. Soc. Am. J. 40, 647–651.
- 659 Robain, H., Descloitres, M., Ritz, M., Atangana, Q.Y., 1996. A multiscale
 660 electrical survey of a lateritic soil system in the rain forest of Cameroon. J.
 661 Appl. Geophys. 34, 237–253.
- 662 Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005.
 663 Electrical resistivity survey in soil science: a review. Soil Tillage Res. 83,
 664 173–193.
- 665 Sanglerat. G, The penetrometer and soil exploration, Elsevier, 1975.
- 666 Stokoe, K. H., II, Wright, G. W., James, A. B., and Jose, M. R., 1994,
 667 Characterization of geotechnical sites by SASW method, *in* Woods, R. D., Ed.,
 668 Geophysical characterization of sites: Oxford Publ.

669 Stuedlein, A. W., 2010. Shear-wave velocity correlations for Puyallup River
670 alluvium, J. Geotech. and Geoenviron. Engng. 136, 1298 (2010);
671 doi:10.1061/(ASCE)GT.1943-5606.0000342 (7 pages)

672 Sturtevant, K. A., Baker, G. S., Snyder, C., Kopczynski, S., 2004.
673 Hydrogeophysical characterization of bedrock fracture orientations using
674 azimuthal seismic refraction tomography. AGU, H23A-1122.

675 Sykora, D. E. and Stokoe, K. H. (1983). "Correlations of in-situ measurements
676 in sands of shear wave velocity," *Soil Dyn. Earthq. Eng.*, 20, 125–36.

677 Sykora, D. W. and Koester, P. J. (1988). "Correlations between dynamic shear
678 resistance and standard penetration resistance in soils," *Earthq. Eng. Soil*
679 *Dyn.*, 2, 389–404.

680 Tarantola, A., 1987, Inverse problem theory. Elsevier Science Publishing Co.,
681 Inc.

682 Tengberg A, Stocking M, Dechen SCF. 1997. The impact of erosion on soil
683 productivity - An experimental design applied in Sao Paulo State, Brazil,
684 *Geografiska Annaler Series A, Physical Geography* 79A (1-2) 95-107.

685 Thompson, J.A., Bell, J.C., 1996. Color index for identifying hydric conditions for
686 seasonally saturated mollisols in Minnesota. *Soil Sci. Soc. Am. J.* 60,
687 1979–1988.

688 Ulugergerli, U. E. and Uyanik, O. (2007). "Statistical correlations between
689 seismic wave velocities and SPT blow counts and the relative density of
690 soils," *J. Test. Eval.*, 35, 1–5.

691 U.S. Department of Agriculture, 2003. National Soil Survey Handbook, title 430-
 692 VI. [Online] Available: [bhttp:// soils.usda.gov/technical/handbook/N](http://soils.usda.gov/technical/handbook/N).

693 Van-Camp. L., Bujarrabal, B., Gentile, A-R., Jones, R.J.A., Montanarella, L.,
 694 Olazabal, C. and Selvaradjou, S-K. (2004). Reports of the Technical
 695 Working Groups Established under the Thematic Strategy for Soil
 696 Protection. EUR 21319 EN/1, 872 pp. Office for Official Publications of the
 697 European Communities, Luxembourg.

698 [Webb, TH, Lilburne, LR. 2005 Consequences of soil map unit uncertainty on](#)
 699 [environmental risk assessment AUSTRALIAN JOURNAL OF SOIL](#)
 700 [RESEARCH 43 \(2\), 119-126](#)

701 Williams, B.G., Hoey, D., 1987. The use of electromagnetic induction to detect
 702 the spatial variability in the salt and clay content of soils. *Austr. J. Soil Res.*
 703 25, 21–27.

704 World Reference Base, 1998. World Reference Base for Soil Resources. FAO,
 705 World Resources Report no. 84, Rome, Italy.

706 Xia, J., Miller, R.D., and Park, C.B., 1999, Configuration of near surface shear
 707 wave velocity by inverting surface wave: *Proceedings of the symposium*
 708 *on the application of geophysics to engineering and environmental*
 709 *problems '99*, 95–104.

710 Ye L., Van Ranst E. 2009. Production scenarios and the effect of soil
 711 degradation on long-term food security in China, *Global Environmental*
 712 *Change* 19 464–481.

713 Zhou. S, Caractérisation des sols de surface à l'aide du pénétromètre
714 dynamique léger à énergie variable type Panda, thèse, université Blaise-
715 Pascal, Clermont-Ferrand-2, 1997, 179 p.
716

717 **7. Tables**

718

719 Table 1. Soil properties for 4 drilling observations along the n°5 transect with a
720 spacing of 40 m in the middleslope and 20 m in the downslope (Figure 1). θ :
721 water content, ρ_r : real density, ρ_b : bulk density, ThickLM: thickness of the loamy
722 material horizon, Depth: sample depth, Depth Bis: replicate sample depth.

723

724 Table. 2. General statistics (Min: minimum; Max: maximum; Av: average;
725 Median; Stdev, standard deviation; Var: variance; CV, coefficient of variation;
726 Skwe, skewness; Kurt, kurtosis for *ThickLM*, which is the thickness of the loamy
727 material horizon (m); Q_d : the mechanical resistance (MPa).

728

729 **8. Figure captions**

730

731 Figure 1. Location of the study plot within the Bourville catchment in Normandy,
732 a region of Northern France. Contour lines of absolute altitude with 0.5 m
733 intervals within the 120×130 m plot are presented for the 157 data points of the
734 seismic survey. Position of the 4 drilling events and the 12 penetrometer
735 soundings are indicated along the n°5 transect.

736

737 Figure 2. Loamy sediments showing the critical thickness are rendered more
738 vulnerable to runoff and water erosion relative to competent and nearly
739 outcropping clays enriched with flints.

740

741 Figure 3. a) Photograph of the towing system with the seismic acquisition
742 central and laptop computer. b) Photograph of the seismic array with 24
743 geophones regularly spaced at 50 cm. c) Schematic representation of the
744 acquisition configuration with the key parameters: near offset x_0 , geophone
745 spacing Dx and offset range L .

746

747 Figure. 4. Workflow diagram illustrating the methodology using to obtained
748 reliable Vs versus depth models.

749

750 Figure 5. a) Example of recorded surface waves. b) Observed dispersion curve
751 obtained by $Cf-f$ domain transformation. c) Comparison between the initial and
752 final Vs versus depth model obtained after the inversion step. d) Comparison
753 between observed and synthetic dispersion curves. The relatively good fit
754 between these curves indicates the reliability of the final model.

755 Figure 6. Qualitative comparison between a drilling observation, a penetrometer
756 sounding and a Vs versus depth model at the same location. The relatively
757 good correlations between Vs, mechanical properties of the soil and the
758 observed lithologies are shown.

759

760 Figure 7. Representation of the Vs distribution. Two populations characterised
761 by Gaussian laws of $\text{mean}_{1\text{st layer}} = 171 \text{ m.s}^{-1}$, $\sigma_{1\text{st layer}} = 80 \text{ m.s}^{-1}$ and of $\text{mean}_{2\text{nd}}$
762 $\text{layer} = 347 \text{ m.s}^{-1}$, $\sigma_{2\text{nd layer}} = 76 \text{ m.s}^{-1}$ are distinguished.

763

764 Figure 8. Seismic and penetrometric sections along transect n°5. Threshold
765 values of Vs=240 m/s and Qd=20 MPa overlay the sections in black dotted line
766 and red solid line, respectively. Drilling observations overlay the seismic section
767 in black crosses. There is a good agreement, in terms of *ThickLM*, between the
768 threshold values and *ThickLM* obtained from drilling observations.

769

770 Figure. 9. Observed V_s after exclusion filtering ($V_s > 240$ m/s) versus averaged
771 interpolated Qd computed for the thicknesses of V_s intervals on 1D models
772 along the n°5 transect.

773

774 Figure 10. a) Spatial variations in the thickness of the loamy material horizon
775 (*ThickLM*) obtained using MASW. b) Spatial variations in the stiffness of the
776 loamy material horizon (*StiffLM*) obtained using Eq. (2). Contour lines of
777 absolute altitude with a 0.5 m interval overlay the map. The 4 drilling
778 observations, 12 penetrometric data points and 157 seismic data points are
779 shown on the map. The black dotted line represents the buried former gully that
780 is visible in the photograph. c) Photograph showing the buried former gully.

781

782 Figure 11. a) Directional variogram of *ThickLM*. b) Directional variogram of
783 *StiffLM*.

784

785 Figure 12. Plot of estimated *ThickLM* values obtained using the MASW
786 methodology and the observed *ThickLM* for the 4 drilling observations.

787

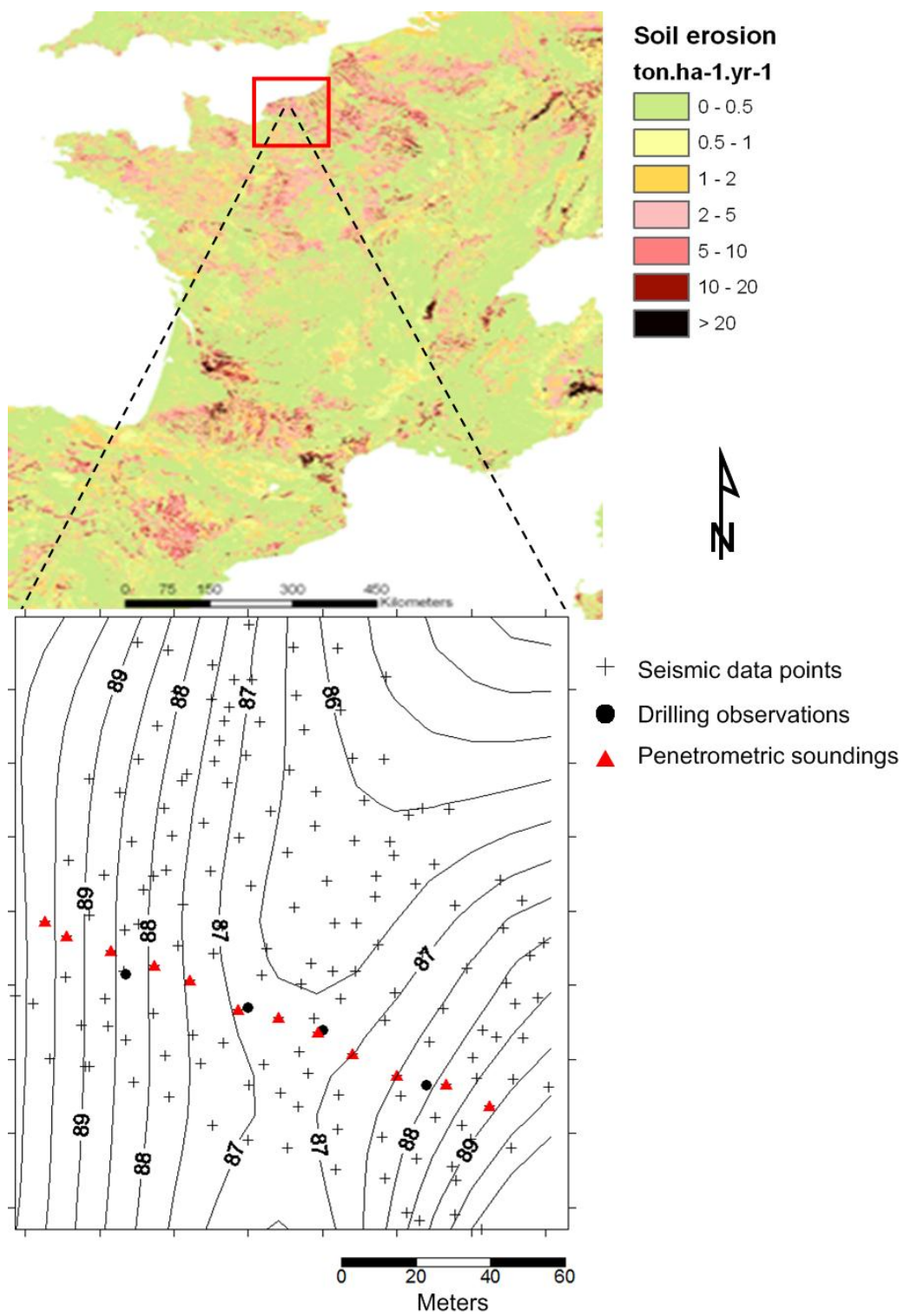
788

789

790

791

792 Figure 1



793

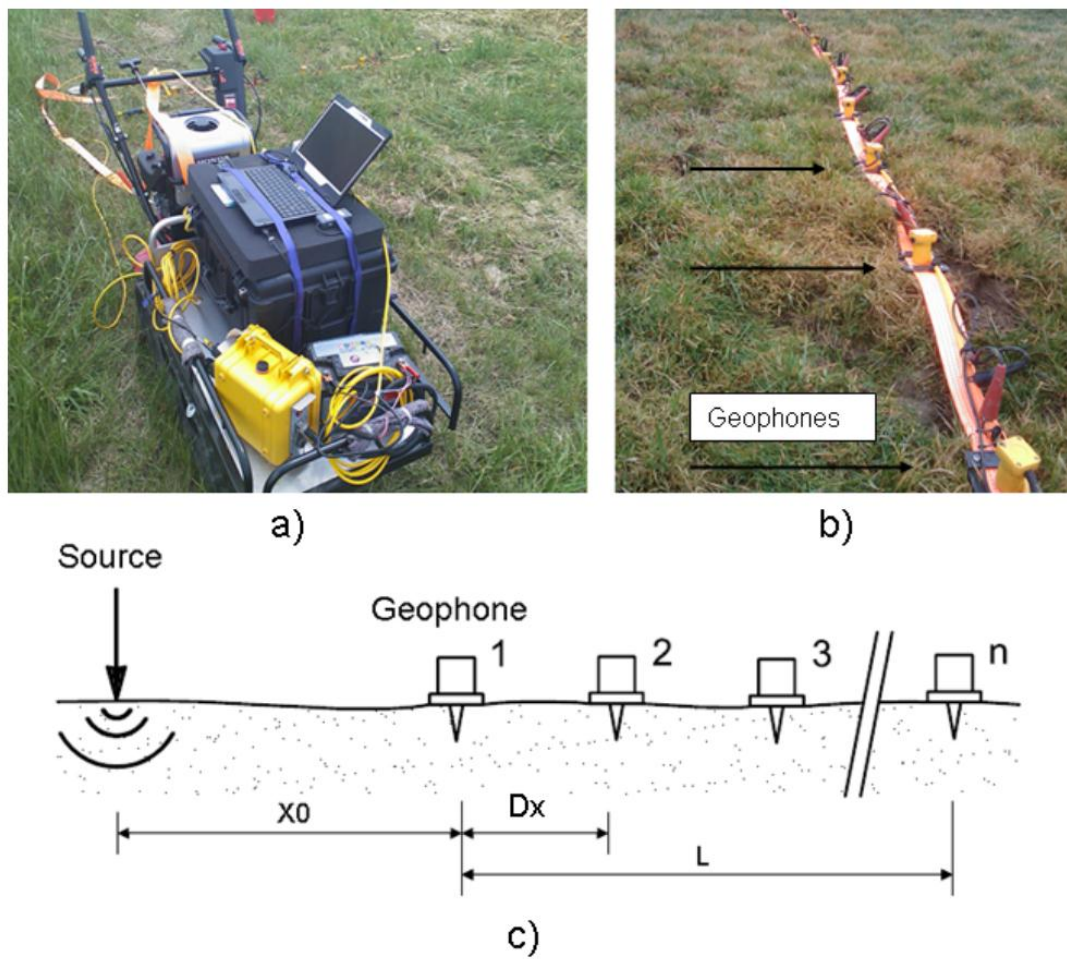
794 Figure 2



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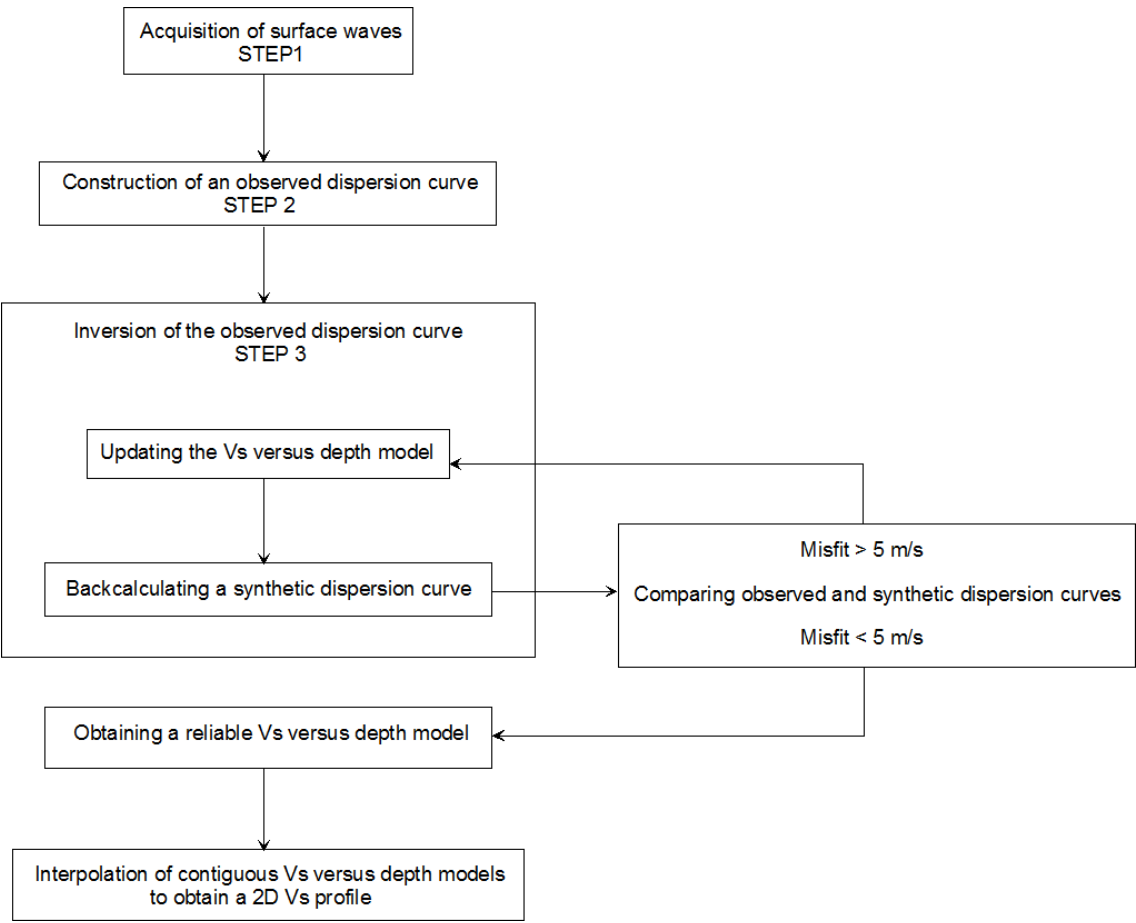
797 Figure 3



798

799

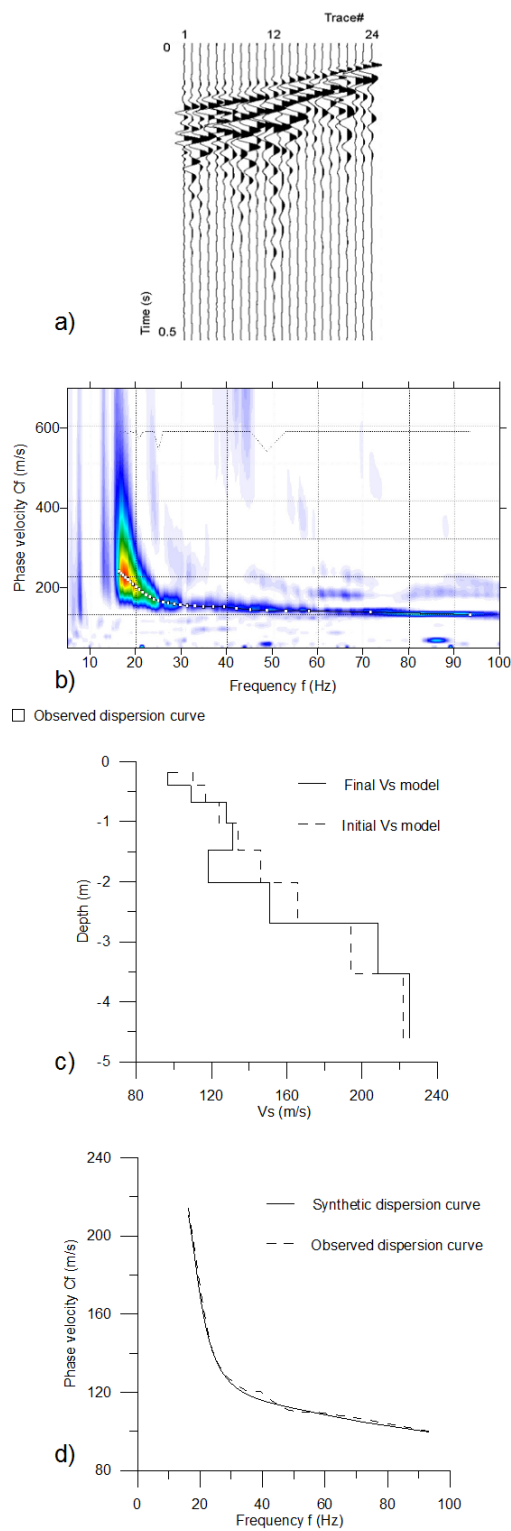
800 Figure 4



801

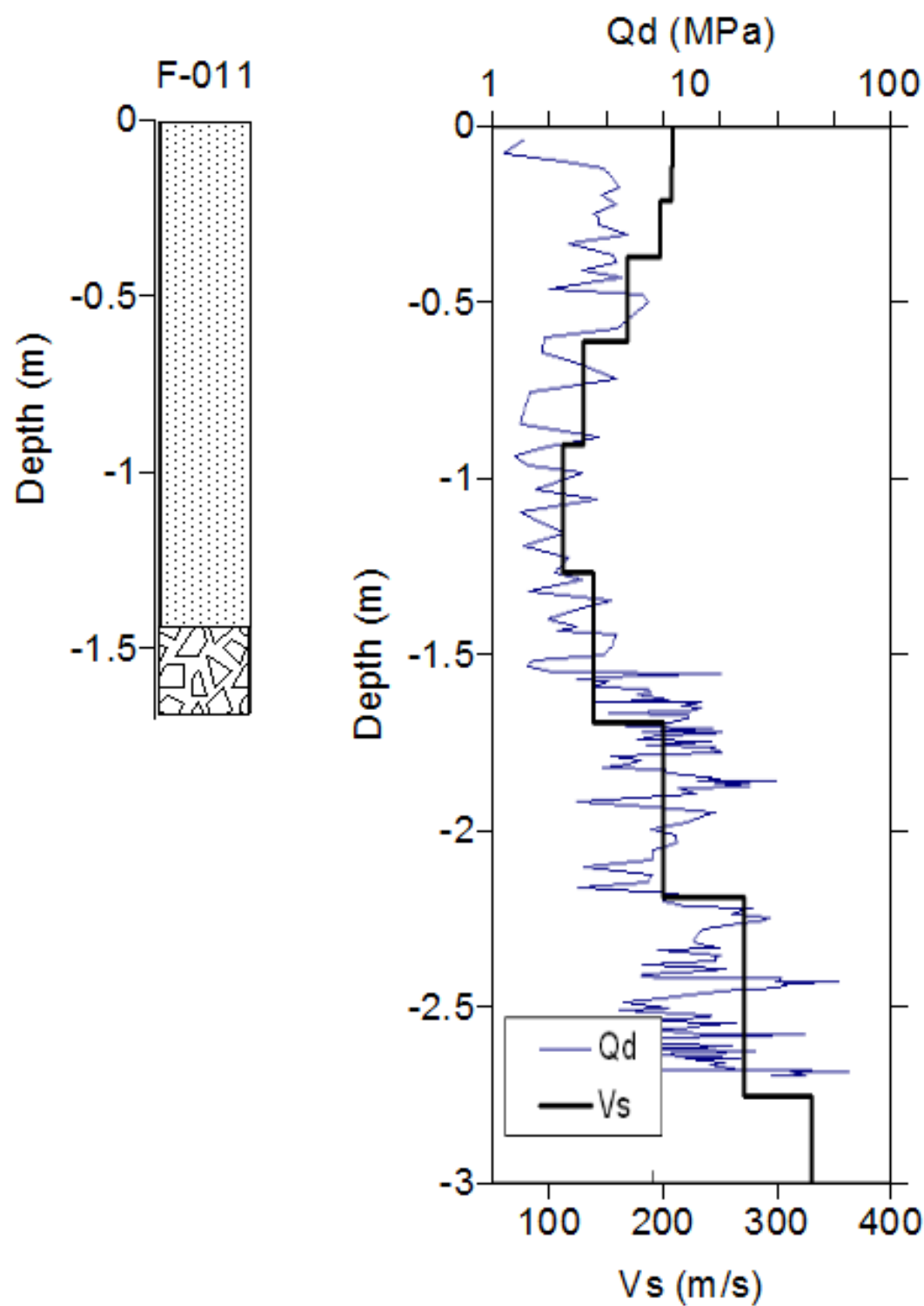
802

803 Figure 5



804

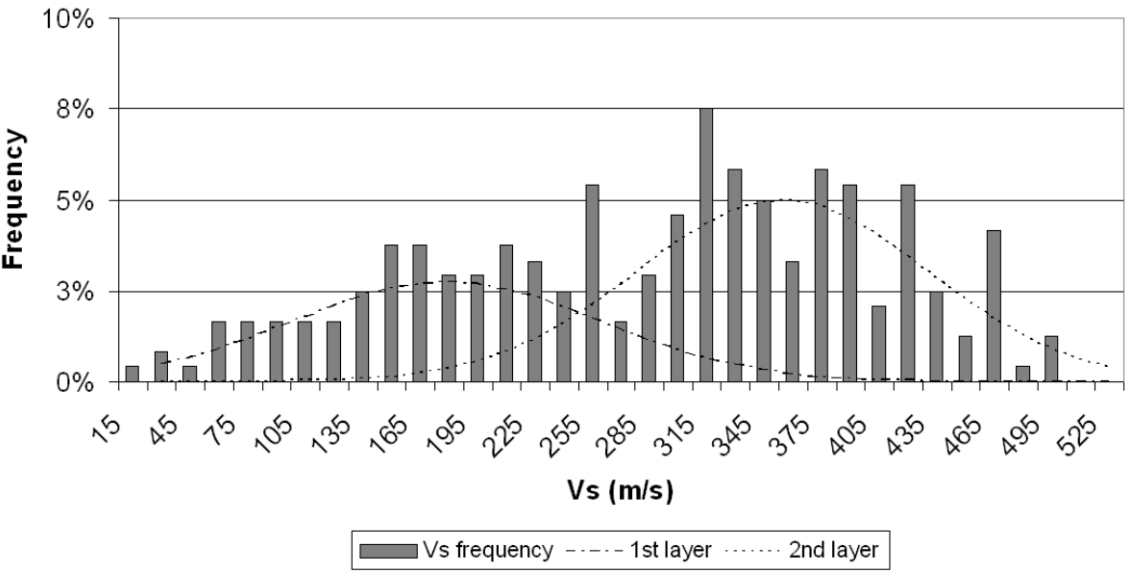
806 Figure 6



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808

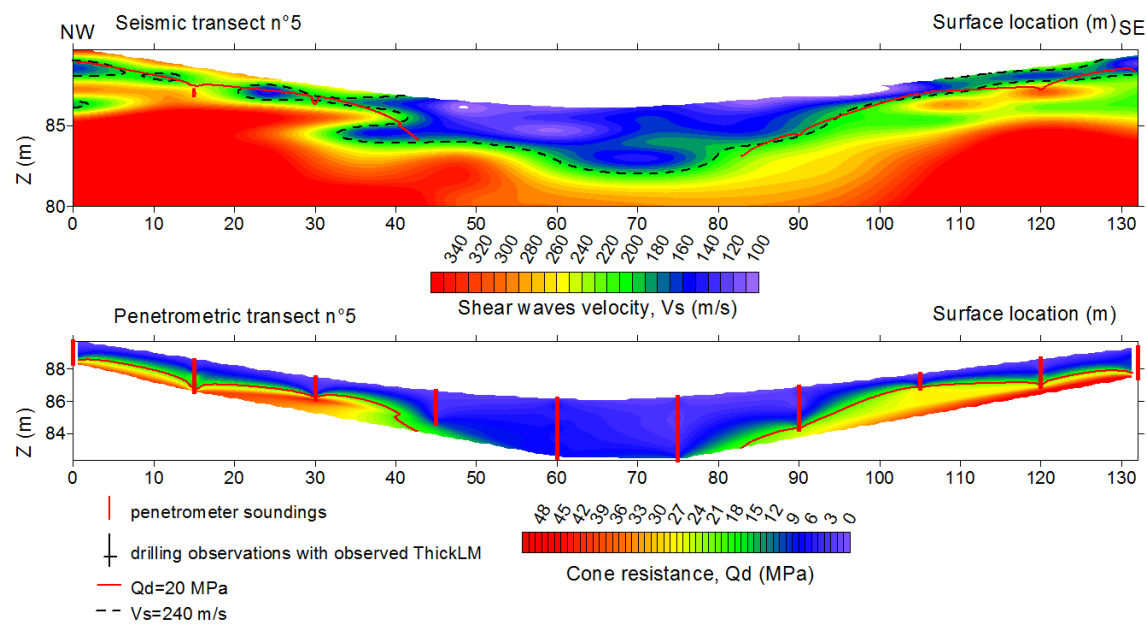
809 Figure 7



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811

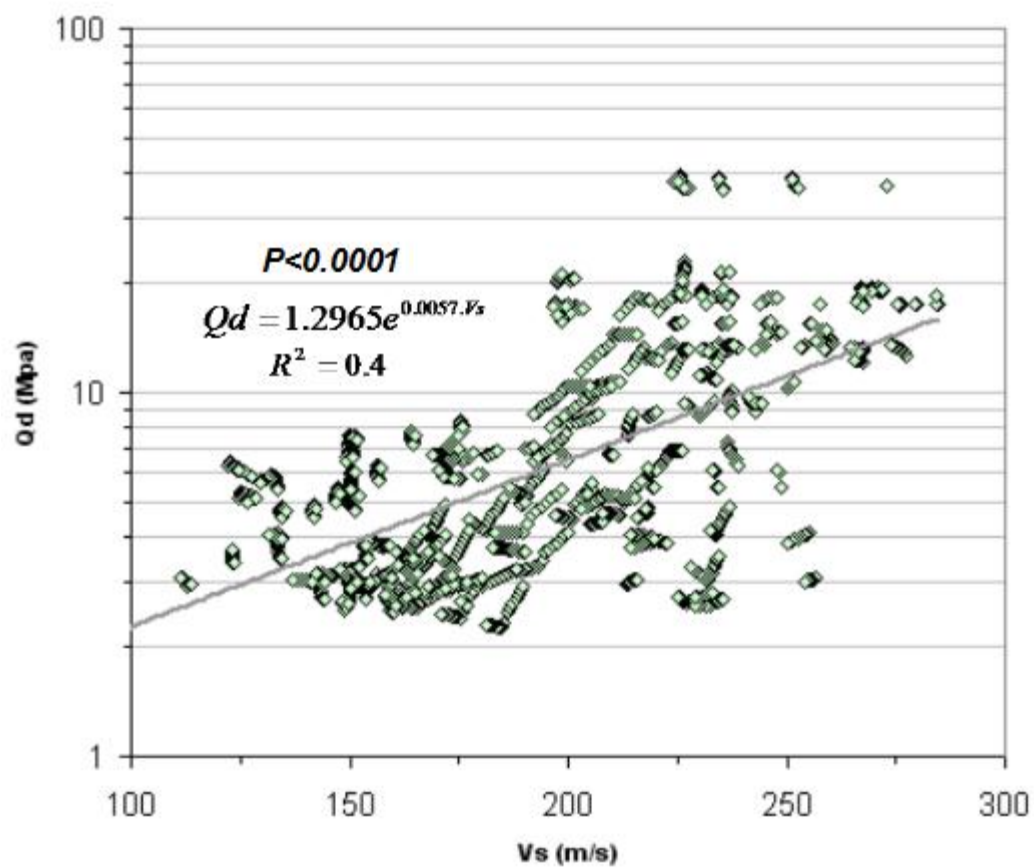
812 Figure 8



813

814

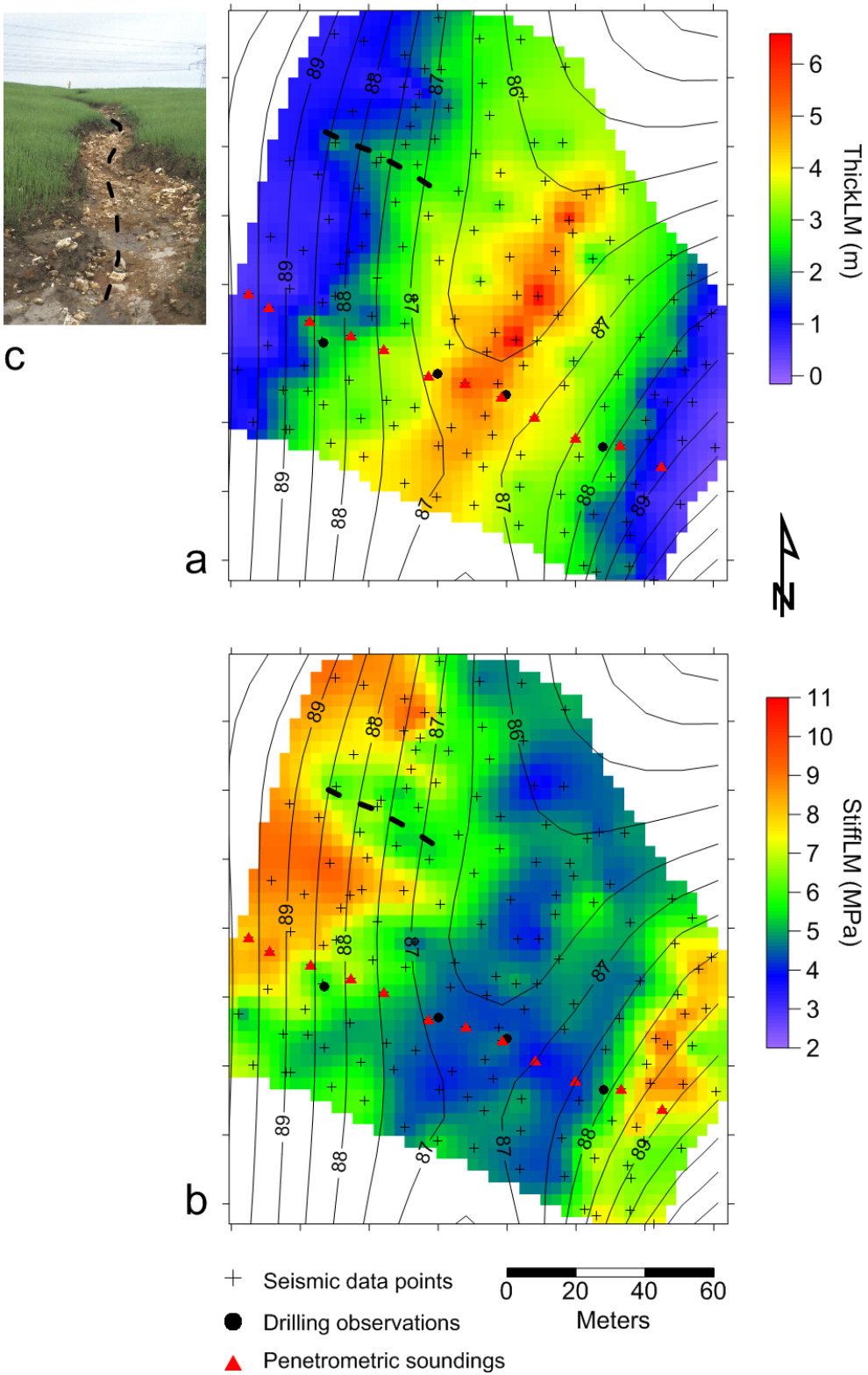
815 Figure 9



816

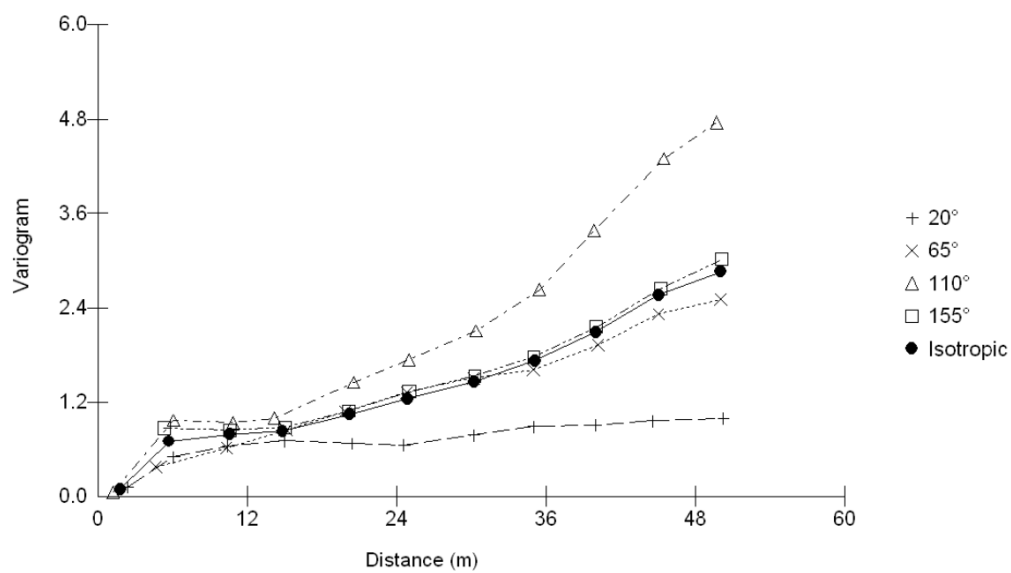
817

818 Figure 10

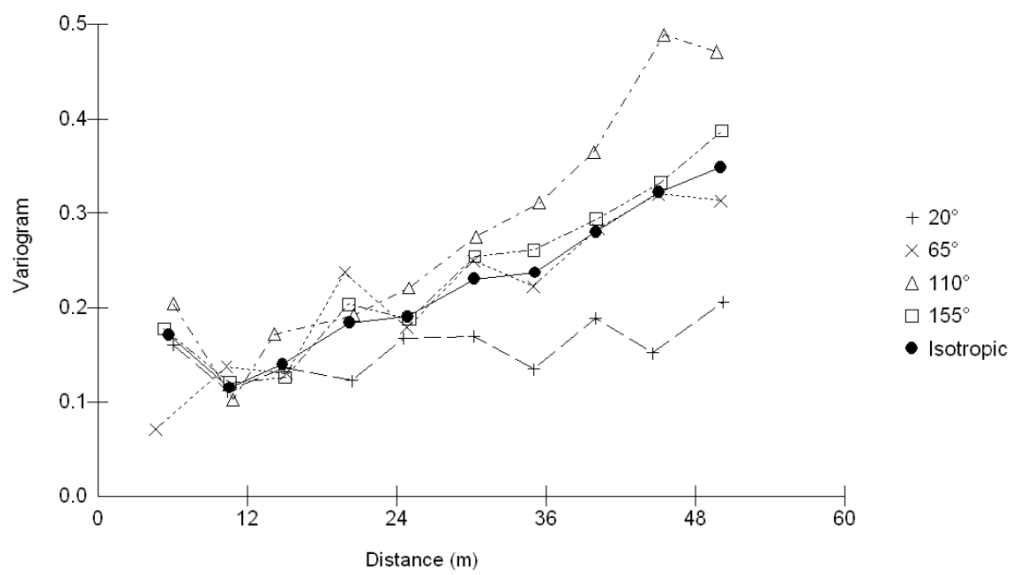


819

821 Figure 11



a

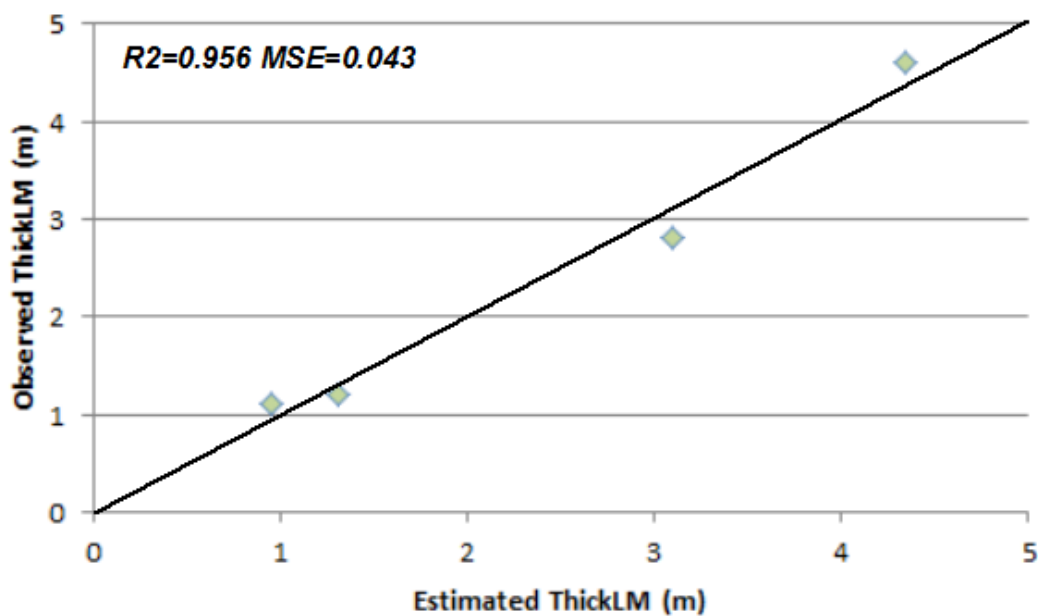


b

822

823

824 Figure 12



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