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1 **Complementary dense datasets acquired in a low-to-moderate seismicity area for**
2 **characterizing site effects: application in the French Rhône valley.**

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30 ABSTRACT

31 Superficial geological layers can strongly modify the surface ground motion induced by
32 an earthquake. These so-called site effects are highly variable from one site to another
33 and still difficult to quantify for complex geological configurations. That is why site-
34 specific studies can greatly contribute to improve the hazard prediction at a specific site.
35 However, site-specific studies have historically been considered difficult to carry out in
36 low-to-moderate seismicity regions. We present here seismological datasets acquired in
37 the framework of the French-German DARE project in the heavily industrialized area
38 surrounding the French Tricastin Nuclear Site (TNS). TNS is located above an ancient
39 canyon dug by the Rhône River during the Messinian period. The strong lithological
40 contrast between the sedimentary fill of the canyon and the substratum, as well as its
41 expected confined geometry make this canyon a good candidate for generating site
42 effects which are variable on short spatial scales. In order to investigate the impact of
43 this geological structure on the seismic motion, we conducted complementary seismic
44 campaigns in the area. The first main campaign consisted of deploying 400 nodes over a
45 10x10 km area for one month and aimed at recording the seismic ambient noise. A
46 second seismic campaign involved the deployment of 49 broadband stations over the
47 same area for more than eight months. This complementary campaign aimed at
48 recording the seismicity (including local, regional and teleseismic events). These
49 different designs allowed us to target a variety of seismic data, at different spatial and
50 temporal scales. Beyond the interest for local operational seismic hazard applications,

51 these datasets may be valuable for studying seismic wave propagation within complex
52 km-scale sedimentary structures. In this paper we present the deployment designs as
53 well as initial analyses to provide information on the characteristics and the overall
54 quality of the data acquired to future users.

55 INTRODUCTION (EXPERIMENT MOTIVATION):

56 It is well-known that superficial geological layers can strongly modify the surface ground
57 motion induced by an earthquake. Soil properties in the vicinity of the Earth's surface
58 generally become softer leading to an amplification of the seismic motion. In the case of
59 complex geological structures, such as sedimentary valleys, seismic waves can be
60 trapped and the geometry of the soft deposits will further affect the ground motion by
61 increasing both the duration and amplitude of the shaking (e.g. Bard and Bouchon,
62 1985; Kawase, 1996; Semblat et al., 2005). These so-called *site effects* are a source of
63 particular concern for Seismic Hazard Assessment (SHA), as they can greatly increase the
64 level of seismic hazard in critical zones located on sedimentary basins such as big cities
65 (e.g. Mexico City, Mexico; Los Angeles, USA; Tokyo, Japan; Grenoble, France) or
66 industrialized areas with critical infrastructure.

67 By being related to local conditions, site effects are highly variable from one site to
68 another and still difficult to quantify for some geological configurations (e.g. deep
69 valleys or canyons). Recent studies (e.g. Pilz and Cotton, 2019) have for example
70 confirmed the limitation of 1D models to predict site amplifications. That is why site-

71 specific studies can greatly contribute to improve the hazard prediction at a specific site
72 in comparison to ergodic estimates based on data from global databases. However, they
73 have historically been considered difficult to carry out in low-to-moderate seismicity
74 regions where moderate to large earthquakes have long return periods.

75 The French-German project *Dense ARray for seismic site effect Estimation - DARE* (IRSN;
76 Univ. of Potsdam; GFZ Potsdam; Univ. Grenoble Alpes), funded by the French and
77 German Research Agencies, aims to propose new approaches based on the acquisition
78 of dense in-situ datasets for the estimation of site effects (and the application of site-
79 specific studies) in low-to-moderate seismicity regions. The contribution and interest of
80 innovative methods, combining, in particular, dense array acquisition and the use of
81 seismic ambient noise will be investigated within the framework of site effect studies.
82 The DARE project targets the heavily industrialized area of the widespread Tricastin
83 Nuclear Site (TNS) in the French Rhône valley. TNS is located on the deep and elongated
84 Messinian Rhône Canyon. This canyon was dug about 6 million years ago during the
85 Messinian Salinity Crisis (MSC) in the Mesozoic substratum (Cretaceous limestones and
86 sandstones). This canyon is filled with Pliocene marine and continental sediments (sands
87 and clays) nowadays covered by the Rhône Quaternary terrace (Holocene). Lithological
88 information from boreholes reaching the bedrock and preliminary geophysical
89 campaigns indicate that the canyon can reach locally >500 m and is deeply incised (Gélis
90 et al., 2022). The strong material contrast between the sedimentary fill and the
91 substratum (estimated V_s contrast around 3 from Gélis et al., 2022), as well as its
92 expected confined geometry make this canyon a good candidate for generating site

93 effects. Gélis et al. (2022) have reported local ground-motion amplification reaching a
94 factor of 6 for some frequencies on top of the canyon relative to nearby Cretaceous
95 limestone outcrops, using about one year of continuous recordings. This first study
96 quantifies the seismic amplification associated with the presence of the canyon at two
97 sites on top of the sediment canyon. One of the objectives of the DARE project is to
98 extend this estimation to the scale of the sediment canyon in order to catch the spatial
99 variability of the amplification caused by this complex geometric structure.

100 It is worth noting that the interest of studying this area has been brought to the
101 forefront with the occurrence of the Mw4.9 Le Teil earthquake. This event took place on
102 November 11, 2019 about 20 km north of TNS and severely damaged several villages in
103 the vicinity of the rupture area (Ritz et al., 2020; Cornou et al., 2021). It corresponds to
104 the most destructive and strongest earthquake in metropolitan France since 1967. This
105 event highlights the issue of the seismic hazard in the region and brings a new
106 dimension to the DARE project (launched and funded before the occurrence of this
107 earthquake).

108 In the framework of the DARE project we conducted two complementary seismic
109 campaigns. The first campaign, carried out by IRSN with the help of EGIS and SISPROBE
110 companies, consisted of deploying more than 400 all-in-one seismic nodes over a 10x10
111 km area for one month (winter 2020). This campaign targeted the recording of seismic
112 ambient noise generated by both global and local sources (Froment et al., 2023). To
113 complement this first acquisition, a second seismic campaign was carried out by the 4
114 partners of the DARE project. This second campaign consisted of deploying about 50

115 broadband stations over the same area for more than eight months (September 2020 -
116 May 2021) and aimed to record the seismicity (including teleseismic events, local and
117 regional seismicity) (Pilz et al., 2021).

118 These two experiments provide complementary datasets with different temporal and
119 spatial scales, targeting different observables (ambient noise; seismicity). Seismic
120 ambient noise will be used as an alternative seismic data whose exploitation deserves to
121 be encouraged in the estimation of seismic amplification due to site effects. This is
122 particularly true in low-to-moderate seismic areas such as France and Germany where
123 seismic campaigns may turn out to last long before catching enough seismicity to get
124 statistically robust results; thereby limiting the widespread use of an empirical
125 estimation of site effects in an operational context. These complementary datasets will
126 make it possible to propose and compare alternative methods for site effect estimation;
127 evaluate their interests, uncertainties and limitations. The density of instruments
128 considered in these 2 experiments will help to 1) provide high-resolution imaging of the
129 medium and 2) to capture the variability and multi-dimensional features of the site
130 effects related to the expected complex geometry of the geological structure. It will
131 therefore increase the resolution of the local site-specific study. The implication of such
132 study in SHA will be investigated by comparing the site-specific site responses derived in
133 the DARE project from extensive datasets and 3D medium characterization, with those
134 from ergodic approaches (e.g. based on site proxies) or 1D modelling that are commonly
135 used in SHA studies especially in low-to-moderate seismicity areas. This valley is also
136 representative of deep valleys whose amplification cannot be correctly predicted from

137 surface geophysical or geotechnical parameters (e.g. Vs30) alone. Taking into account
138 the effects of valley thickness and configuration is currently an important topic of
139 discussion in the groups in charge of seismic standards (e.g. Paolucci et al., 2021) and
140 the new version of the European Seismic building code (2021-draft) introduces explicitly
141 a further “F” category for deep soil deposits ($H_{800} > 100$ m). The data acquired in this
142 experiment will contribute to a better understanding of the factors that control site
143 effects. This will help to validate and improve, for such “deep valleys” site classes,
144 building codes amplification factors and also identify the best parameters (proxies) for
145 predicting them and reduce the variability of potential site response within site classes.

146 This extensive seismic campaign will provide a deep knowledge on the way the
147 geological structure impacts the seismic motion in the area of Tricastin where some
148 critical infrastructure is located. It is worth noting that studies are also underway to
149 build a 3D accurate geological model of the area (Bagayoko, M.Sc. thesis, 2021). These
150 various approaches and data will contribute to produce an extensive characterization of
151 the medium and the seismic motion, of great interest for the study of site effects.

152 The direct contribution of such seismological acquisitions in terms of SHA as well as the
153 occurrence of the Le Teil earthquake in the area enhance the interest of the 2 acquired
154 datasets at a national scale beyond the initial framework. Moreover, to the best of our
155 knowledge, such complementary dense arrays have not been deployed so far at such
156 spatial scale in Metropolitan France and Germany, increasing their interest at the
157 national scale.

158 Beyond the local or even national interest, these datasets provide extensive
159 observations on a km-scale western European sedimentary basin. Continuous advances
160 in seismic instrumentation, storage and computation capacities will favor similar
161 campaigns in the future. Repeating the same kind of acquisition to other European
162 structures (with a similar scale and context) will reveal to what extent they show
163 common features. Results can then help to define how to consider the impact of such
164 structures in seismic regulations or guides. They can also be confronted to what we
165 know from worldwide sedimentary basins, in different contexts or at different scales
166 that may dominate global databases. Again, this would help understand the conditions
167 of applications and limitations of the use of ergodic approaches.

168 For all these reasons, these datasets (Pilz et al., 2021; Froment et al., 2023) will be made
169 available to the scientific community at the end of the DARE Project (see Data and
170 Resources section).

171 INSTRUMENT DEPLOYMENT

172 TARGET ZONE

173 In 2019, when the DARE project was initiated, the local geology of the Messinian canyon
174 remained poorly documented in the region of Tricastin. Gélis et al (2022) provide some
175 first insights about the canyon rims and the subsurface characteristics locally.
176 Lithological information from boreholes in the area (BSS-Infoterre Underground

177 database) combined with a thorough geological study allowed them to approximately
178 locate the canyon rims in the area (Figure 1). Moreover, the same borehole data and 1D
179 geophysical medium characterization provide local knowledge about the nature and
180 characteristics of the sedimentary canyon fill and bedrock. In particular, Gélis et al.
181 (2022) show that the base of the canyon deepens southward, consistently with the
182 Rhône flow direction, reaching a depth of at least 500 m at a distance of 2-to-3 km to
183 the south of TNS (in the vicinity of site BOLL in Figure 1(a)). At this location, the canyon
184 bottom incises or at least, lies directly on top of Urgonian (lower cretaceous) limestones.
185 Finally, in the same area, it has been deduced that the canyon is particularly narrow,
186 with an E-W width that is not greater than 4 km.

187 From these first observations, we targeted a 10 km by 10 km area surrounding the
188 imprint of Pliocene and Quaternary sediment deposits and TNS (Figure 1). This
189 extension allows us to embed nearby outcrops of cretaceous series incised by the
190 canyon and that constitutes the basement of the canyon sedimentary fill.

191 It is worth noting that most of this target zone is located in a heavily industrialized area
192 including the widespread TNS, a hydroelectric dam and 5 towns (>45 000 inhabitants). It
193 is also crossed from north to south by several railroads (including freight lines and the
194 high-speed TGV train), the busy A7 highway and N7 national road. A map displaying this
195 infrastructure is given in the electronic supplement (Figure S1). Many cultivated fields
196 can also be found in the central part of the target zone. Quieter environments can be
197 found at the eastern and western edges of the zone. It is worth noting that the spatial
198 distribution of noisy and quiet environments matches approximately the geological

199 setting: noisy environments are rather located in the valley, i.e. on top of the
200 sedimentary canyon, whereas quiet environments are rather located on surrounding
201 foothills, i.e. on cretaceous outcrops-.

202 NODE DEPLOYMENT

203 Preliminary experiment: Noise Test

204 IRSN with the help of EGIS and SISPROBE companies, had the objective to deploy about
205 400 all-in-one seismic nodes over our target area to record the seismic ambient noise
206 for one month. Before this massive deployment, a smaller scale campaign was carried
207 out to investigate the feasibility, constraints, limitations of the planned dense ambient
208 noise experiment. In particular, this so-called *noise test* aimed to investigate the quality
209 of continuous measurements and the characteristics of seismic noise in the area in
210 order to refine the design of the 400-instrument experiment. In this context, we
211 deployed 30 3-component Geospace GSX nodes (with 5-Hz GSC-3C-LF geophones,
212 sampling frequency of 250 Hz) following a spiral-shaped array over the 10 km x 10 km
213 zone (Figure 1(a)). This design allowed us to sample a wide range of interstation
214 distances and azimuths. The center (and denser) part of the spiral is located in the
215 southeastern part of the target zone where the Messinian canyon is expected to be the
216 deepest and the narrowest (Gélis et al., 2022) and where we planned to densify the 400-
217 node deployment. These 30 nodes were deployed on November 5, 2019. This noise test
218 was supposed to last for one week. However, on November 11, the Mw4.9 Le Teil
219 earthquake occurred at about 20 km north of the 30-node array. The noise test array

220 thus kept installed one more week, that is, until November 19. The selection of a high
221 gain for the instrument response to measure background vibrations was not appropriate
222 for motions as strong as the one generated by the Le Teil earthquake on the array. The
223 recordings were thus clipped on most of the 30 nodes preventing usual ground motion
224 analysis.

225 During this preliminary experiment, broadband Guralp CMG6-TD instruments were also
226 co-located with nodes at 3 sites (see Figure 2(a) for a picture of co-located instruments).
227 These 3 sites were previously instrumented during temporary campaigns since 2016
228 (Gélis et al., 2022). Originally, they were called BOLL, PAUL and ADHE in reference to the
229 names of the localities where they were deployed. BOLL and PAUL are located on top of
230 the Messinian Canyon while ADHE is located on nearby cretaceous outcrops (Figure
231 1(a)). ADHE has been considered as a local reference rock site for the estimation of
232 seismic amplification associated with the presence of the canyon at BOLL and PAUL
233 (Gélis et al., 2022). It is worth noting that these 3 historical sites have been
234 instrumented during all the acquisitions carried out in the DARE project using different
235 instrumentation. Table 1 summarizes information (naming and instrumentation) relative
236 to these 3 historical sites for the different acquisitions. The co-location of nodes and
237 CMG6-TD instruments allowed us to investigate the ability of node recordings to
238 reproduce broadband station recordings especially at low frequencies (i.e. below the
239 cut-off frequency of 5 Hz). This is detailed in the section discussing the quality of the
240 nodal dataset.

241 Noise correlation functions computed over this whole test array revealed a clear
242 propagation as well as the dispersion of surface waves over a large frequency range
243 from 0.1 to a few Hertz (~ 8 Hz). This covers the frequency range of interest for our
244 study, including the fundamental resonance frequency f_0 of the canyon (~ 0.5 Hz at BOLL,
245 Gélis et al., 2022) and frequencies higher than 1 Hz for SHA and engineering
246 applications. The design of the 400-node experiment has been refined following the
247 analysis performed on the noise test array. The final design shown in Figure 1(b) is a
248 compromise between 1) the need to cover the entire area of interest (array aperture),
249 2) the desired resolution (interstation distance) and 3) the number of instruments
250 available. Note that a similar analysis has been conducted on the final dataset (400
251 nodes) and some results are shown in the section discussing the quality of the nodal
252 dataset.

253 Main Campaign

254 After the preliminary experiment, 409 nodes were deployed during the main campaign.

255 The node array design for the main deployment is a combination of 5 sub-arrays:

- 256 - a loose grid covering the entire area composed of 164 nodes following East-West
257 shifted lines of some 10 nodes. Node separation in this loose grid ranges from
258 400 to 1300 m and averages about 800 m.
- 259 - a denser grid located 2-to-3 km south of TNS, expected to cover the narrowest
260 part of the Messinian Canyon as deduced by Gélis et al. (2022). This denser grid

261 is composed of 179 nodes spaced 200 to 250 m apart, deployed along roads and
262 rural tracks.

263 - 2 dense East-West Lines following 2 roads designed to provide a denser coverage
264 of the northern part of the study area, where the sedimentary fill is expected to
265 be broader than in the southern part. The northern (resp. southern) line is
266 composed of 29 (resp. 31) nodes separated by about 400 m.

267 - 6 more nodes were deployed out of our target area. One of these distant nodes
268 was placed right on La Rouvière fault that broke during the Le Teil earthquake.
269 The five others were deployed a few km away from our zone covering different
270 azimuths. These sensors may be used as distant virtual sources (seismic
271 interferometry applications) to illuminate the array with incoming wavefield
272 from different directions.

273 It is worth noting that the first 2 digits of the station codes correspond to the codes of
274 these sub-arrays. Further explanation about the station codes used for the 2 node
275 deployments (preliminary noise test and the massive campaign) is given in electronic
276 supplement.

277 We used the same 3-component Geospace GSX nodes as the ones deployed during the
278 noise test. The nodes have been installed on public land, that is, mainly along roads. The
279 deployment took place from February 17 to February 20, 2020. Instruments remained
280 on field for one month and were de-installed between March 16 and 18. 402 nodes have

281 been retrieved. 23 of them were found unburied. The data of the last days are therefore
282 not exploitable for these nodes.

283 BROADBAND STATION DEPLOYMENT

284 To complement the first dense and short-term campaign, a second campaign was
285 carried out. This second campaign consisted in deploying 49 broadband stations over
286 the same target area (Figure 1(c)) for at least six months and aimed at recording the
287 seismicity, including local, regional and teleseismic events. 47 sites were instrumented
288 with DATA-Cube³ and 3-component Trillium compact 120s, and 2 sites were
289 instrumented with Guralp CMG-6TD. Of the total 49 stations, 3 were deployed in sites
290 that have been instrumented since 2016 (Table 1): BOLL (E01 in this survey) was
291 instrumented with a DATA-Cube³ and a Trillium Compact 120s, while PAUL and ADHE
292 (E04 and G06 in this survey, respectively) were instrumented with Guralp CMG-6TD. All
293 stations recorded continuously with a sampling frequency of 100 Hz. Installation sites
294 were chosen following several criteria:

- 295 - Intent of catching the spatial ground motion variability expected from the overall
296 geometry of the sedimentary valley (middle versus edges of the valley, small
297 versus large sediment thickness);
- 298 - Instrumentation of different “rock” sites that could be considered as reference
299 for the estimate of the amplification due to the sedimentary canyon. This implies
300 the instrumentation of outcrops of various geological series, the canyon dug
301 into. We finally instrumented 4 sites located on Urgonian hard limestones

302 (Lower Cretaceous formation in Figure 1) covering different azimuthal directions
303 (A04 and A06 to the West, G06 to the East and D06 to the north). We also
304 instrumented Miocene outcrop (G03) of the Saint-Restitut hill made of ten to
305 twenty meters of calcareous sandstones. Note that this site is located on a high
306 topography that could generate some topographic site effects. Other sites such
307 as F02, and G01 have been settled on Cretaceous marly sands and sandstones
308 (Upper Cretaceous formation in Figure 1). Near La Garde-Adhémar village, C06
309 was installed on Oligocene lacustrine limestones.

- 310 - The rest of the stations were deployed on the recent quaternary fluvial terrace
311 (generally 10-20 m thick) overlying the Pliocene fill of the Messinian canyon or
312 locally Upper Cretaceous marls, sands and sandstones (Lapalud town area);
- 313 - As for the node experiment, we instrumented the La Rouvière fault by installing
314 3 stations (RFN, RFC and RFS) along the rupture of the Le Teil earthquake;
- 315 - Sites as quiet as possible (by trying to get the station installed as far as possible
316 from obvious noise sources);
- 317 - Satellite visibility for GPS-controlled clocks;
- 318 - Priority to free-field installations to limit the impact of the structure on the
319 recorded motion. Only 2 sites were finally located inside buildings (A0 in a school
320 and G4 in the city hall of Saint-Paul-3-châteaux).

321 - In total, 8 stations of the broadband deployment correspond to sites which have
322 been also instrumented during the node experiment. In addition to the 3
323 “historical” sites listed in Table 1, The 5 other sites are listed in Table 2.

324 The array was installed between September 14 and September 18, 2020 and de-
325 installed at the end of May 2021 (May 25-27). About half of the sites were located on
326 private property. For most of the sites, sensors have been buried in free field and placed
327 over a small concrete plate base. For a few sites, the sensor could not be buried, either
328 because it was located inside buildings – sites A0 and G4 (Figure 2(g)) – or because the
329 site was located on very hard limestone slab – site A4 (Figure 2(b))–. For the latter case,
330 the sensor was placed at the surface and protected by a bucket filled with some foam
331 thermal insulation. For each station, we used 2 pasture fence batteries (9V- 160 Ah)
332 connected in series. This installation was designed to power the station for at least 6
333 months (i.e. the duration initially planned) but was expected to allow for a longer
334 experiment. We finally decided to keep the installation for more than 8 months. Given
335 the displacement restrictions due to the covid-19 pandemic during the experiment, we
336 went on field for maintenance only once throughout these 8 months (end of January
337 2021). During this maintenance visit, we collected the data and checked the overall
338 installation. We re-installed 2 stations that were found unburied and changed some
339 batteries showing a low voltage.

340 NODAL DATASET: OVERALL QUALITY AND INITIAL

341 OBSERVATIONS

342 GENERALITIES ABOUT THE DATASET

343 The data were resampled at 50 Hz leading to a total volume of about 1 TB for the main
344 campaign and about 20 GB for the noise test. These data will be made publicly available
345 in Fall 2023 on the French RESIF datacenter. A FDSN network code (XG) and a DOI
346 (<https://doi.org/10.15778/RESIF.XG2020>) have been assigned (Froment et al., 2023).

347 DATA COMPLETENESS

348 For the nodes that were found unburied, we visually checked the data to identify the
349 day the sensor was dug up and we removed the files corresponding to days after that
350 date from the dataset. Over the 400 nodes retrieved, 46 nodes (i.e. 11,5%) provide an
351 incomplete dataset between the end of the deployment (February, 20) and the
352 beginning of the deinstallation (March, 16). All these cases correspond to a premature
353 stop in recording (no intermediate gaps were observed). Figure 3(a) shows the
354 availability for these 46 nodes (the rest of the dataset is complete over the experiment
355 duration). The overall data collection reaches more than 96% of completeness between
356 February 20 and March 16.

357 COMPARISON BETWEEN NODE AND BROADBAND RECORDINGS

358 This section focuses on the evaluation of the performance of the easy-to-deploy nodes,
359 in particular below the instrument's natural frequency of 5Hz. Previous studies have
360 discussed this aspect, for example within the SRL focus section on Geophone Array
361 Seismology (e.g. Karplus and Schmandt, 2018). To address this issue in our context, we
362 perform a comparison between signals recorded by co-located node and broadband
363 CMG6-TD during the preliminary *noise test* experiment at ADHE. It is worth noting that
364 BOLL was also instrumented with a Trillium compact sensor during the second
365 campaign. Figure S2 in the electronic supplement shows also a comparison of PPSDs
366 between the 2 broadband instrumentations involved in our experiment, although the
367 recording period is different (November 2019 and 2020).

368 Using data from the noise test dataset allows us to compare waveforms of the Le Teil
369 local earthquake. Figure 4 (a) and (b) shows a waveform comparison between the two
370 instrumentations on November 11, 2019 (Le Teil earthquake, (a) ; 5-min noise window,
371 (b)). Signals have been corrected from the respective instrument's response. Guralp
372 CMG6-TD have been corrected using their own station calibration information.
373 Regarding the nodes, a common correction has been applied for the whole pool
374 deduced from instrument characteristics (frequency, gain). The earthquake waveforms
375 filtered between 0.2 and 20 Hz recorded by the 2 instruments show a very good
376 agreement both in phase and amplitude. A small discrepancy in amplitude is visible on
377 the vertical component. This is explained by a slight clipping on this component for the

378 CMG6-TD. This comparison suggests that the GMG6-TD and the node recorded nearly
379 identical waveforms down to frequencies much lower than 5Hz. As an example, a similar
380 comparison for an aleatory 5-min noise window picked during nighttime is also shown
381 (Figure 4(b)). This shows that the very good agreement between recordings is not
382 limited to large-amplitude signals but is still observed for low-amplitude noise.

383 We also computed probabilistic power spectral densities (PPSD) using 1-hour windows
384 with no overlap, over the 2 weeks of recording. Figures 4(c) and (d) show the PPSD for
385 the two instruments at ADHE. Overall, the PPSD of the nodes for 1-hour windows match
386 the broadband seismometer in shape. In detail, we can distinguish 3 ranges of
387 frequency. For frequencies higher than 0.2 Hz, the comparison between the two
388 instruments is very good. In this frequency range, the noise level is quite low at ADHE,
389 due to its location on hard rock (no amplification due to geology) and in an isolated,
390 very quiet area. Between 0.1 and 0.2 Hz, the PPSDs remain quite similar between the
391 two instruments but show some slight differences. At low frequency (below 0.1 Hz), the
392 noise level is getting higher than the New High Noise Model (NHNM, from Peterson,
393 1993) for the two instruments. On the horizontal components, one may see the
394 influence of an imperfect protection from environmental changes and of the resulted
395 tilt changes. Figure S2 shows that this effect is also observed on the Trillium Compact.
396 On the vertical component, the noise level is slightly lower but the absence of variation
397 suggests that the instrumental noise dominates in this band for the two instruments.
398 Note that the overall noise level is significantly higher at BOLL (see Figure S2 in the
399 electronic supplement) because of the location of this site (on top of the sedimentary fill

400 whose local resonance frequency is about 0.5 Hz and within an industrialized
401 environment).

402 Our different observations show that node signals reproduce CMG-6TD signals down to
403 0.2 Hz in terms of waveform comparison (local M4.9 earthquake and low-amplitude
404 ambient noise) and statistics of 1-hr noise window amplitude. This analysis supports the
405 possibility to exploit the node recordings at frequencies lower than 5 Hz. This result is of
406 particular importance within the framework of the DARE project since it aims at
407 characterizing the seismic site response (frequency range $\sim 0.1-10$ Hz), within a
408 sedimentary canyon whose fundamental resonance frequency is significantly below 5 Hz
409 (~ 0.5 Hz). This instrumentation comparison was a key aspect in the analysis of the
410 preliminary noise test before the launch of the massive experiment.

411 DATASET CONTROL QUALITY

412 In order to get a rapid overview of the continuous recording at each node, we built a
413 catalogue gathering different representations of the monthly seismic signal (temporal
414 waveform, spectrogram and spectral density on 10-minute segments). This catalogue
415 provides an easy way to explore basic features of the dataset. This makes it possible to
416 identify signals and/or nodes presenting obvious issues (Figure 5 shows the catalogue
417 sheets for ADHE, BOLL and a node presenting major issues). By doing this, we identified
418 less than 1% of the 1-month recordings as unusable (as the example shown in Figure 5 -
419 top row-). For the rest of the dataset, we consider that the 1-month recording may be
420 analyzed at least for part of the 10-minute segments and/or in a limited frequency

421 range. Labelling the quality of seismic signals is not trivial since it is strongly application-
422 dependent. Therefore, we do not go further here quantifying the quality of the data
423 since this needs to be addressed in relation to specific applications and will come with
424 associated studies based on these data. The complete catalogue (i.e. for the 400 nodes)
425 for the North, East, and vertical component is available respectively in Files S1, S2 and
426 S3 in the electronic supplement.

427 Note that the analysis of this catalogue was the basis to investigate the impact of
428 numerous cultural noise sources in this industrialized area on the continuous data. This
429 is the scope of ongoing work within the DARE project (Gisselbrecht et al., submitted to
430 Geophysical Journal International).

431 PROPAGATION RECONSTRUCTED FROM NOISE CORRELATION FUNCTIONS

432 Figure 6 presents stacked sections of noise correlation functions (NCFs) computed for all
433 the station pairs of the 400-node array. This representation is useful to give an estimate
434 of distance ranges over which one can expect to extract coherent wavefields at different
435 frequencies. To compute NCFs, continuous data were first split into 30 min segments.
436 Each segment was then spectrally whitened. NCFs were computed for each 30-min
437 segment and then stacked over the entire recording time (1 month). Averaged seismic
438 sections shown in Figure 6 are constructed by binning NCFs in fixed distance intervals
439 (every 100 m). Note that symmetrized NCFs are plotted, that is, the mean of the
440 negative and positive lag-times. Figure 6 reveals the wave propagation reconstructed

441 from NCFs in 2 frequency bands (0.1-1 Hz; 1-10 Hz) and at 2 spatial scales (the entire
442 array and the denser part in the southeastern zone of the array).

443 At low frequency (i.e. <1Hz, Figure 6 - top panel), one can observe a clear propagation
444 over regional distance (25 km; i.e. between the node located on La Rouvière fault and all
445 the other nodes) with a frequency content dominated by the secondary microseismic
446 peak. On the TT component, higher frequencies (0.5-1 Hz) are visible revealing the
447 dispersion of Love waves, as well as more complex patterns associated with the
448 propagation over the first 10-12 km (i.e. the core of our target zone). The middle panel
449 in Figure 6 shows that the propagation of waves at frequencies higher than 1 Hz can be
450 tracked on the stacked NCFs over about the same distance (10-12 km) but is clearer over
451 a distance of about 5 to 6 km. NCFs computed only on the densest part of the array
452 allows us to zoom in on shorter distances (Figure 6 – bottom panel). One can clearly see
453 the dispersion of both Rayleigh (ZZ, RR components) and Love (TT component) waves.
454 Multiple branches (multiple modes), ruptures in slopes (rapid changes in velocities, see
455 for example around 3-3.5 km) and differences on the different components reveal a
456 complex medium. It is worth noting that the interpretation of these sections in terms of
457 structure is limited since this spatially averaged representation mitigates propagation
458 patterns due to lateral heterogeneities.

459 BROADBAND DATASET: OVERALL QUALITY AND INITIAL

460 OBSERVATIONS

461 GENERALITIES ABOUT THE DATASET

462 The broadband dataset acquired in this study has already been uploaded into the
463 GEOFON data archive under network code Y7 (Pilz et al., 2021). Free access to this
464 dataset will be available at the end of the DARE project (end of 2023). The complete
465 dataset has a size of 463 GB and includes the data for all usable broadband stations (one
466 station has been tagged as faulty, see discussion in the next section), with a sampling
467 rate of 100 Hz.

468 DATA COMPLETENESS

469 The temporal availability of the broadband data is shown in Figure 3(b). It is good in
470 general terms, taking into account the originally planned duration of 6 months for the
471 deployment. During the field maintenance trip in January 2021, we used the available
472 spare equipment to replace the batteries of the stations that were reporting the lowest
473 voltages (B00, D01, D03, E02 and G03). The new batteries allowed these stations to
474 keep recording for up to 2 months longer than originally planned. Some 20 stations con-
475 tinued to operate for the entire period from September 2020 to the end of May 2021.
476 Considering this 8-month time period, data availability varies significantly from 99.18%
477 (D00) to 19.73% (A06), with an average of 77.62%. The most important data gaps not

478 related to battery failure belong to stations A06, B00 and B01 and B02. In the case of
479 A06, an important part of the records was lost probably due to a faulty SD card. Station
480 B00 was disconnected after the initial deployment and the sensor was tilted, which was
481 fixed during the field maintenance trip at the end of January, 2021. Station B01 lost
482 power in November and was reconnected during field maintenance. B02 stopped re-
483 cording prematurely in early February 2021 after a flood in the Rhône river drowned the
484 station. The remaining data gaps are much smaller and can mainly be attributed to
485 short, temporary losses of GPS signal or problems when attempting to read the SD cards
486 retrieved from the field. For one station none of the recordings are usable, i.e. A05, and
487 therefore has not been included in the Y7 network in the Geofon data archive.

488 DATASET QUALITY AND INITIAL OBSERVATIONS

489 Reorientation of the broadband seismic sensors

490 Many seismological studies are sensitive to the correct orientation of the horizontal
491 axes of the seismic sensors. However, the equipment that is required to perform a
492 precise determination of the orientation of the horizontal components during field work
493 is often costly and difficult to operate (e.g., Ringler et al., 2013). Therefore, this task is
494 usually accomplished using a magnetic compass, which might introduce non-negligible
495 errors (Wang et al., 2016). It is worth noting that the local declination is $1^{\circ}54'$. To
496 account for the orientation errors in this survey, we have analyzed the arrival angles of
497 teleseismic Rayleigh waves following the approach described by Doran & Laske (2017).
498 Orientation angles are obtained through a grid-search procedure at seven discrete

499 frequencies between 0.01 and 0.04 Hz in order to minimize any possible bias caused by
500 the local laterally heterogeneous earth structure.

501 The angles obtained for the North component of the broadband stations, measured
502 clockwise from true north, are shown in Figure 7 and listed in Table S1 in the electronic
503 supplement. Most sensors were correctly oriented during installation as shown by the
504 average deviation of 9.3°, with only few stations showing deviations higher than 15°
505 (A01, B00, C01, C04, G06, E04).

506 Noise levels across the broadband array

507 The main purpose for the broadband array deployment was to survey the seismicity. In
508 general, the quality and utility of seismic data is strongly dependent on the background
509 ambient noise levels at each site. This is particularly true for industrialized regions such
510 as our study area. To characterize the ambient noise levels at each of the broadband
511 array sites, we divided one month of continuous records into 1-hour segments with half-
512 hour overlap and computed the power spectral density (PSD) for each segment. Then,
513 we created spectrogram-like plots showing the temporal variation of the PSDs for the
514 three components (examples are shown in Figure 8). We used these spectrogram-like
515 plots as the features for a k-Means clustering algorithm (e.g. Lloyd, 1982) with the aim
516 of classifying each site based on the overall noise levels. This analysis allowed us to
517 identify three types of sites: 1) overall low noise levels, 2) high noise levels at short
518 periods (< 1 s), and 3) high noise levels both at short (< 1 s) and long periods (> 30 s).
519 Note that the spectral content of the broadband recordings will be discussed in terms of

520 periods (i.e. in seconds) in the following. The top left panel in Figure 8 shows the
521 variation of the PSD over time for an example of each type of site: A04, E03 and D04 for
522 sites of type 1), 2) and 3), respectively. At short periods (< 1 s) the PSDs show a clear
523 daily and weekly pattern, related to human activity (e.g., Groos and Ritter, 2009). At
524 periods ranging from approximately 2 to 8 seconds, the microseismic frequency band
525 can clearly be identified in all stations. The intensity and frequency range of the
526 microseismic noise varies with time and increases towards the winter months. In the
527 long period range (> 30 s) the characteristics of the noise are site-dependent and do not
528 show any clear temporal patterns. The highest levels of noise at long periods appear
529 predominantly in the horizontal components (HHE and HHN), with practically all stations
530 showing higher noise levels than the NHHM (Peterson, 1993), and increase steadily with
531 increasing period. Long period noise with similar characteristics has often been
532 interpreted as the result of seismometer tilting, i.e. tilting of the sensors from the level
533 position by a certain angle (e.g., Rodgers, 1968; Wielandt and Forbriger, 1999; Rhode et
534 al., 2017). Tilt sources can be varied, ranging from changes in atmospheric pressure to
535 moving vehicles and buildings under wind load in urban environments (e.g., Rhode et al.
536 2017; Forbriger, 2007).

537 The results of the ambient noise-based clustering are summarized in Figure 8. The map
538 in the top right corner shows the broadband station sites colored by site type. The plots
539 in the bottom row of Figure 8 show the mean of the probabilistic power spectral density
540 function (PPSD) estimated from all the available PSDs for each station. Visual inspection
541 of the mean of the PPSDs also supports the classification of the sites in three different

542 clusters or categories. The correlation between the geographical location of the stations
543 and their noise levels is not completely straightforward and suggests that the noise level
544 is significantly variable at the local scale, probably strongly related to very local
545 environment but also to geology, thereby explaining the observed broadband trends.
546 This is particularly pronounced for the lowest noise levels (e.g. cluster 1, blue color in
547 Figure 8- that shows a very good agreement with areas with no Pliocene sedimentary
548 fill) despite being located in very different environments (i.e. urban environment for
549 D06; isolated clearing in a forest for A04).

On the recorded seismicity

550 After reviewing the ambient noise levels across the broadband array we selected station
551 A04, deployed on a rock site outside of the valley and one of the quietest stations in the
552 array, to elaborate a seismicity catalogue. The starting point was the ISC (International
553 Seismological Centre) catalogue. A criterion based on lower-bound magnitude
554 thresholds (relative to the epicentral distance) was used as a preselection, followed by a
555 signal-to-noise-based selection and finally a visual inspection. The derived catalogue of
556 424 events is given in File S4 in the electronic supplement and illustrated in Figure S3.
557 Note that this catalogue covers the lifetime span of A04 (i.e. until April 2021, see Figure
558 3(b)).

559 Figure 9 shows two examples of the varied seismicity recorded by the broadband
560 network. The first example is a regional earthquake (Mw5.0 from September 30, 2020 in
561 the Pyrenees). The top row in Figure 9 contains two plots showing the event for the

562 complete duration and a close-up of the P-wave onset (Figures 9(a) and 9(b),
563 respectively). The second example belongs to a teleseismic earthquake (Mw6.3 from
564 September 18, 2020 in the Central Mid Atlantic Ridge). The waveforms for the complete
565 duration of this event and a close-up on the P-wave onset are shown in the bottom row
566 in Figure 9 (9(c) and 9(d), respectively). The signal-to-noise ratio of most stations is good
567 for these kinds of events. The noisiest stations are often the ones located in the vicinity
568 of the TNS area, and to the busy A7 highway (e.g. E03, E04, F03).

569 SUMMARY

570 The datasets presented in this paper provide complementary seismic data in terms of
571 spatial and temporal scales as well as instrumentation (a dense 1-month nodal
572 experiment versus a few-month campaign of broadband stations). These different
573 designs aimed at targeting a variety of seismic data and signals, including the recordings
574 of the ambient noise, a local moderate earthquake (the 2019 Mw4.9 Le Teil earthquake)
575 as well as regional and teleseismic seismicity. The first analysis made on these data and
576 gathered in this paper provides information on the characteristics and the overall
577 quality of these data that would be helpful for future users. These complementary data
578 will be used in the framework of the DARE project to characterize the complex local
579 sedimentary structure and its impact on the seismic motion. They will be of great
580 interest to provide an extensive site-specific seismic study related to a deep valley in an
581 industrialized area hosting critical infrastructure. In particular the idea is to consider

582 different approaches based, on one hand, on numerical simulations of the ground
583 motion in a model of the Earth's sub-soil (i.e. numerical approach), and on the other
584 hand, on the direct analysis of recordings of seismic motions to estimate the site effects
585 (i.e. empirical approach); both methods requiring to be constrained by seismic data. We
586 will also benefit from ongoing studies to establish an accurate geological model in the
587 area. More generally, this project has the objective to provide an example of the
588 interest of acquiring and exploiting seismic data for seismic hazard operational
589 applications in low-to-moderate seismicity areas and deep valleys. These datasets will
590 be made available at the end of 2023.

591 DATA AND RESOURCES

592 The nodal dataset (Froment et al., 2023; doi: <https://doi.org/10.15778/RESIF.XG2020>)
593 will be in free access on the French RESIF datacenter (<https://www.resif.fr/en/>) at the
594 end of the DARE project (end of 2023). The broadband dataset (Pilz et al., 2021; doi:
595 <http://doi.org/10.14470/L27575187372>) will be in free access on the German GEOFON
596 datacenter (GEOFON Y7 Seismic Network (<https://geofon.gfz-potsdam.de/>)) also at the
597 end of 2023.

598 The python Toolbox ObsPy was used for processing the seismological data (Beyreuther
599 et al., 2010). The ArcGis Software was used for map representations.

600 Supplemental Material for this article includes:

601 - A map showing the main anthropogenic elements of the area

- 602 - A description of the station codes used for the nodal deployment
- 603 - A comparison of PPSDs between the broad-band instrumentations used in these
- 604 seismic campaigns (i.e. Guralp CMG6-TD and Trillium Compact+DATA-Cube3)
- 605 - The Quality Control catalog built for the nodal dataset
- 606 - A table listing the estimated error in the orientation of the N-component
- 607 - The catalogue of seismicity recorded at A04 station during the broad-band
- 608 campaign

609 DECLARATION OF COMPETING INTERESTS

610 The authors declare no competing interests

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744

745 Table 1: Information (naming and instrumentation) for the 3 « historical » sites
 746 instrumented during all the acquisitions mentioned in this study.

747

	Site 1	Site 2	Site 3
Coordinates	44.3743°N ; 4.7697°E	44.3467°N ; 4.7357°E	44.3010°N ; 4.7199°E
Historical acquisitions (2016-2019) Naming [<i>instruments</i>]	ADHE [<i>Guralp CMG6-TD</i>]	PAUL [<i>Guralp CMG6-TD</i>]	BOLL [<i>Guralp CMG6-TD</i>]
DARE Noise Test	ADHE [<i>Guralp CMG6-TD</i>] + 60026 [<i>Geospace GSX node</i>]	PAUL [<i>Guralp CMG6-TD</i>] + 60029 [<i>Geospace GSX node</i>]	BOLL [<i>Guralp CMG6-TD</i>] + 60012 [<i>Geospace GSX node</i>]
DARE Acquisition 1 (Nodes)	10011 [<i>Geospace GSX node</i>]	16042 [<i>Geospace GSX node</i>]	03085 [<i>Geospace GSX node</i>]
DARE Acquisition 2 (Broadband)	G06 [<i>Guralp CMG6-TD</i>]	E04 [<i>Guralp CMG6-TD</i>]	E01 [<i>DATA-Cube + Trillium</i>]

748

749

750

751 Table 2: Information regarding the common sites instrumented during the 2 main
 752 acquisitions of the DARE project. These 5 sites are in addition to the 3 historical sites
 753 listed in Table 1. The bottom row gives the approximate distance between the
 754 instruments deployed during the 2 acquisitions.

755

	Site 1	Site 2	Site 3	Site 4	Site 5
Coordinates of Broadband Site	44.5240°N; 4.6574°E	44.3016°N; 4.6706°E	44.3029°N; 4.6941°E	44.3778°N; 4.6981°E	44.2889°N; 4.7334°E
Naming in DARE Acquisition 1 (Nodes)	50006	25073	03041	10006	03162
Naming in DARE Acquisition 2 (Broadband)	RFC	C01	D01	D06	F01
Approximate Distance (m)	< 5	20	< 5	10	30

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758 LIST OF FIGURE CAPTIONS

759 **Figure 1:** Map of the 3 seismic deployments carried out. The left figure shows the design
760 of the preliminary noise test (orange markers) as well as the three historical sites
761 (triangles) instrumented by IRSN since 2016. The figure in the middle shows the design
762 of the massive 400-node deployment with a very dense area contoured by the dashed
763 black line. The right figure shows the design of the 49-broadband deployment. Grey
764 markers represent deployed stations at which data turned out to be unusable (faulty
765 stations). Note that the location of the Mw4.9 Le Teil earthquake (November 11, 2019)
766 on La Rouvière Fault is also displayed in the northern part in each plot.

767 **Figure 2:** Co-located Geospace GSX node and Guralp GMG6-TD (a) and different
768 conditions of installation during the broadband campaign (b-g): (b) on hard limestones
769 outcrop preventing burial in the ground (A04); (c) on a residential neighborhood (G00);
770 (d) in the remote garrigue (C06); (e) in the town of Pierrelatte (D06); (f) in a farm (B06);
771 (g) in the city Hall of Saint Paul Troix Châteaux (G04).

772 **Figure 3:** (a) Temporal availability for the 46 nodes that stopped before the
773 deinstallation of the massive node-deployment (the rest of the array operating correctly
774 for the duration of the experiment). The dashed vertical lines (and thick grey line on top
775 of the figure) show the beginning and end of common recording period for the complete
776 array. (b) Temporal availability for the seismic stations deployed during the broadband
777 campaign. Light grey lines represent unusable data from faulty stations. For clarity, only

778 the vertical components have been displayed.

779 **Figure 4:** Comparison between recordings of a GSX node and a co-located Guralp CMG6-
780 TD at site ADHE. (a-b) Waveform comparison for the Le Teil local earthquake signal (a)
781 and a 5-minute noise window (b). Signals have been filtered between 0.2 and 20 Hz. (c-
782 d) PPSD comparison between the node (c) and CMG6-TD (d) recordings.

783 **Figure 5:** Example of a quality catalogue sheet (North component) for 3 nodes: a node
784 presenting major issued (top), node 03085 located at BOLL site (middle) and node 10011
785 located at ADHE site (bottom). A description of this catalogue is available in the
786 electronic supplement.

787 **Figure 6:** Stacked sections of noise correlation functions (NCFs) computed for all the
788 station pairs of the 400-node array filtered between 0.1 and 1 Hz (top figure) and
789 between 1 and 10 Hz (middle figure). The bottom figure shows the same figure (1-10 Hz
790 filtering) using only pairs of stations located within the densest zone of the deployment
791 (see Figure 1(b)). For clarity only the diagonal components of the NCF tensor are
792 displayed. As indicated in the top right figure, the lines represent velocity lines of 0.25,
793 0.5, 1, 2.5 and 5 km/s.

794 **Figure 7:** Quiver plot showing the orientation of the nominal North component of the
795 broadband sensors deployed in this work. The legend for the geological map is the same
796 as for Figure 1.

797 **Figure 8:** Top left: Example of spectrogram-like plots used as features for the k-Means
798 clustering for three stations (A04, E03 and D04) representing each cluster. Top right: broadband
799 station locations color-coded showing the clustering of the overall ambient noise levels as
800 described in the text. The legend for the geological map is the same as for Figure 1. Bottom row:
801 mean of the overall PDF for all stations for each channel, again colored by cluster. Note that the
802 analysis has not been done for E02 that presents only a few days of usable data (see Figure
803 3(b)).

804 **Figure 9:** Waveforms recorded by the broadband network for a Mw5.0 regional
805 earthquake (Pyrenees; top row) and a Mw6.3 teleseismic earthquake (Central Mid
806 Atlantic Ridge; bottom row). A bandpass filter with corner frequencies 0.05 and 0.5 Hz
807 was applied to the data. The stations are sorted by epicentral distance.

808