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Hydraulic pressure variations of groundwater in the Gran Sasso underground laboratory during the Amatrice earthquake of August 24, 2016

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Abstract

Since May 2015, hydraulic pressure, temperature and electrical conductivity of groundwater have been continuously monitored in the 200 m-long horizontal S13 borehole placed close to the deep underground INFN laboratory (Gran Sasso aquifer, Central Italy). A high sampling rate of the physical quantities up to 50 Hz was achieved with a 3-channel 24-bit ADC. From May 2015 to September 2016 (17 months) we registered hydraulic pressure signals from 12 earthquakes at different surface distances (from 12000 to 30 km) and different magnitudes (from 8.3 to 4.3 Mw). We present the first results obtained for the Amatrice mainshock, comparing the hydroseismograph recorded by the S13 hydraulic pressure device to the time history recorded at the GIGS station, both located in the deep core of the Gran Sasso carbonate aquifer.

I. INTRODUCTION

Coseismic changes of groundwater dynamics have been observed in many places around the world and, Manga and Wang (2015) provide an updated overview of earthquake hydrology, particularly of water table changes during earthquakes. We designed and implemented a system for continuous recording of water pressure, temperature and electrical conductivity of groundwater with a high sampling rate from 10 to 50 Hz; we began continuous recording in May 2015 at a borehole named S13 [Catalano and Salza, 2003] located about 100 meters from the deep underground laboratory of Gran Sasso (LNGS) of the Istituto Nazionale di Fisica Nucleare (INFN).

A seismic station, named GIGS, is located near the S13 borehole (about 200 m-long) within the national underground laboratory of Gran Sasso (LNGS-INFN). The GIGS station, used also in the framework of the GINGER experiment [Simonelli et al., 2016], belongs to the national seismic network of the Centro Nazionale Terremoti of the Istituto Nazionale di Geofisica e Vulcanologia (CNT-INGV), and is equipped with Nanometrics Trillium 240 s and Guralp CMG 3T 360 s seismometers (see also URL http://iside.rm.ingv.it/iside/standard/info_stazione.jsp?page=sta&sta=2571).

II. THE HYDROGEOLOGICAL BACKGROUND

During the L'Aquila earthquake of April 6, 2009 (Mw 6.1, moment magnitude) [Chiarabba et al., 2009], groundwater post-seismic changes (spring discharge, water table, basic hydrochemistry, water isotopes and Radon) of the Gran Sasso aquifer have been studied [Adinolfi Falcone et al., 2012; Amoruso et al., 2011]. The horizontal borehole S13 was selected for the present study because it clearly recorded the water table changes induced by the L'Aquila earthquake [Adinolfi Falcone et al., 2012; Amoruso et al., 2011].

The 1000 km^2-wide Gran Sasso carbonate aquifer is fractured and fault-partitioned. It is formed mainly by slope-to-basin, platform and ramp carbonatic rocks from Upper Triassic to Middle Miocene [Adinolfi Falcone et al., 2006; Barbieri at al., 2005; Catalano et al., 1986] (Fig. 1).

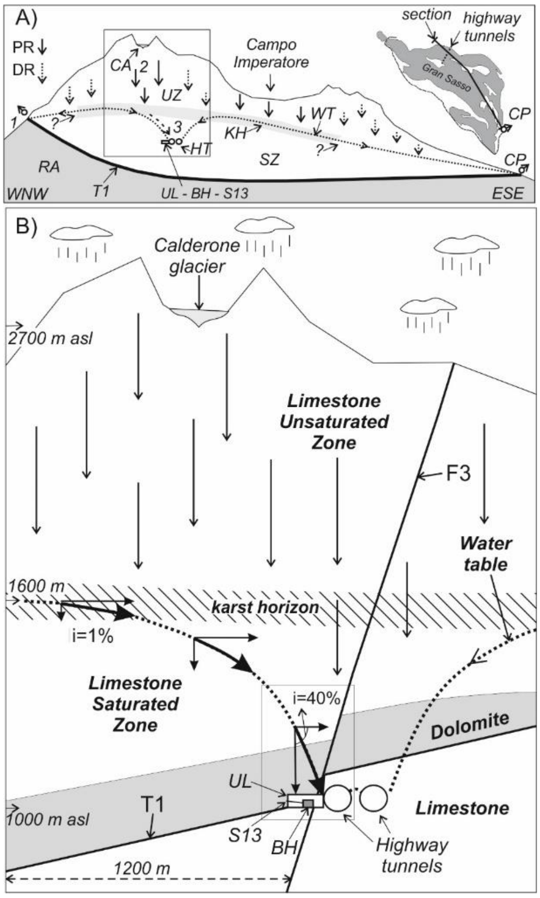

Figure 1: *Scheme A (not in scale) of the Gran Sasso aquifer transversal to the highway tunnels and passing through the UL, BH and S13 area (from Adinolfi Falcone et al., 2008). UZ – unsaturated zone; SZ – saturated zone; KH – karst horizon; RA – regional aquiclude; T1 – permeability boundary (regional thrust); WT – water table; HT – highway tunnels; UL – INFN underground laboratories; CA – Calderone glacier (high elevation water reservoir – preferential recharge area); 1 – overflow spring (CP: Capopescara spring); 2 – preferential groundwater flowpath area; 3 – preferential groundwater flowing toward the UL; PR – preferential recharge; DR – diffuse recharge. The hydrogeological relationships in the square are showed into details in B.*

The Gran Sasso aquifer feeds spring groups, located at low altitude along the low permeability boundary, with a huge discharge of more than 18 m^3/s [Adinolfi Falcone et al., 2008]. Its core hosts the INFN underground laboratories (UL), the Boreholes Hall (BH) and the monitored S13 borehole (Fig. 1).

The Gran Sasso upper thrust (T1) was intercepted in the UL, BH and S13 area (Fig. 1). Drilling of the S13 borehole, located in the BH area, evidenced a very high RQD value (Rock Quality Designation) for footwall limestones, and low discharge values. At the S13 borehole end, high permeability fault rock composed by the Upper Triassic dolomite is placed. It represents the fault zone of the T1 thrust, where, during drilling work discharge values increased up to 15 L/s due to the high permeability of the fault rock, while the hydrostatic pressure exceeded 22 bar due to the low permeability of the dolomitic aquitard [Catalano and Salza, 2003] (Fig. 2).

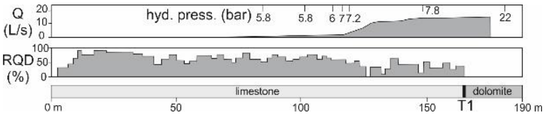

Figure 2: *Data acquired during the boring of S13 (from Catalano and Salza, 2003). Q: drainage discharge (L/s); RQD: Rock Quality Designation (%); hyd. press.: hydraulic pressure (bar). T1 refers to the thrust fault of Fig. 1.*

After the S13 boring, a still tube was installed into it, for a total length of 177 m up to the dolomite.

UL footwall limestones show permeability values of 10^{-7} m/s higher than those of UL hangingwall dolomites as obtained by Lugeon test [Adinolfi Falcone et al., 2008].

The portion of the aquifer drained by the highway tunnels was estimated by considering piezometric data: the five 150 m-long horizontal boreholes (S14-S18) of BH show a piezometric head of around 60 m, whereas S13 shows higher piezometric levels. Hence, the induced hydraulic gradient is around 40% (60 m out of 150 m) an extremely high value due not only to the imposed hydraulic load but also to the low hydraulic conductivity of dolomites [Adinolfi Falcone et al., 2008; Amoruso et al., 2012; 2014].

III. FIRST RESULTS

The area is seismically active [Chiodini et al., 2004; De Luca et al., 2009] and paleoseismic events have occurred in the Gran Sasso chain [Galli et al., 2002].

We decided to monitor the S13 borehole by continuously recording hydraulic pressure, temperature and electrical conductivity at a high sampling frequency using a 3-channel 24-bit ADC, considering the characteristics of S13. The pressure sensor is connected directly to the borehole output, while the other two sensors are fed by groundwater drained into S13 borehole at 1 bar after a pressure reducing device. The hydraulic pressure of S13 borehole varies in the range of 24-28 bar during the year, consistent with a water table above of at least 250-300 m. During the 17 months of recording the water pressure signal followed the sun/moon tides very closely (Fig. 3).

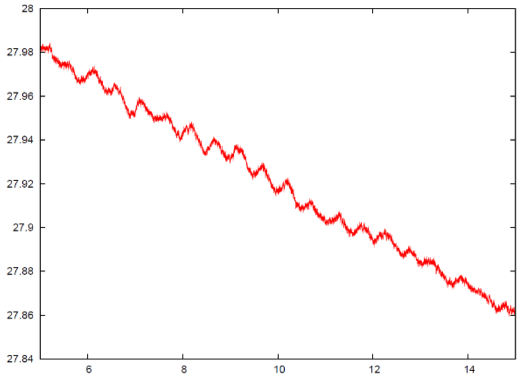

Figure 3: *Hydraulic pressure from 5 to 15 March, 2016; the labels on the vertical scale are bar and on the horizontal scale are the days of March 2016.*

Electrical conductivity did not show any significant variation and the temperature followed both seasonal and daily variations also due to the presence of the close highway tunnel. Following the approach used by Manga and Wang (2015), we searched for coincidences between global seismicity and the hydraulic pressure signals recorded by our device located in the wellhead of the S13 borehole. To this end, we selected global (Mw > 7), regional (Mw > 5) and local earthquakes in the period May 2015 – September 2016 to look at signals in the pressure data.

We found 12 coincidences. As an example, Figure 4 shows the Chile earthquake (Mw 8.3) of September 16, 2015.

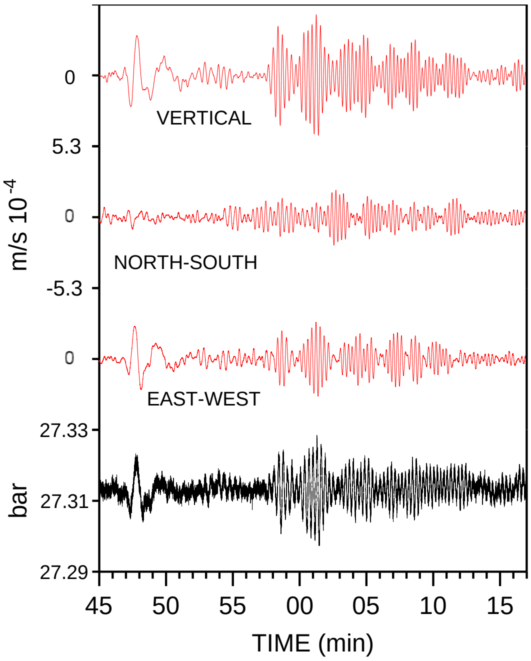

Figure 4: *Chile earthquake of September 16, 2015 (offshore Coquimbo – Mw 8.3). The red traces are the vertical, north-south and east-west components of Trillium 240 s sensor (GIGS) and the black trace is the water pressure signal (arbitrary scale: velocity for the red traces and hydraulic pressure for the black one). Time scale starts from 23:45 (UT).*

More precisely the pressure is sensitive to long-period Love (first arrival) and long-period Rayleigh waves (second arrival) and the signal is very similar to the vertical component of velocity.

Before the Amatrice sequence, we collected only two clear events (Chile Mw 8.3 and Greece Mw 6.5, November 17, 2015). In addition to the main event (Mw 6.0) of August 24, 2016, the pressure sensor detected 9 other signals corresponding to aftershocks ranging from 5.4 to 4.3 Mw.

Figure 5 shows signals for the Mw 6.0 Amatrice earthquake (Central Italy) of August 24, 2016; the waveform is evident and clearly corresponds with the seismic data.

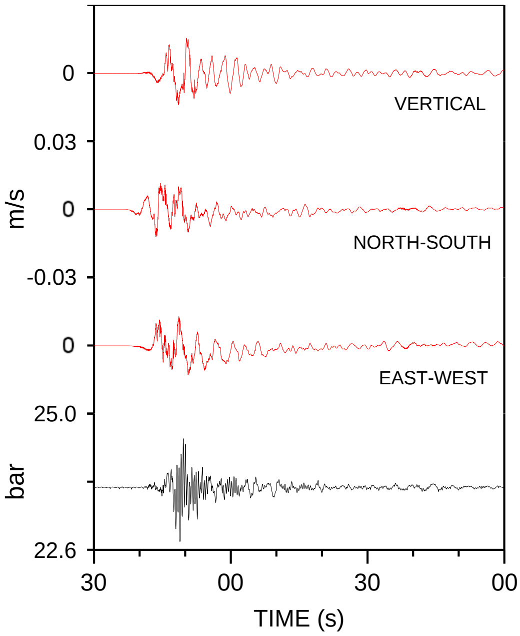

Figure 5: *Amatrice earthquake (Central Italy) of August 24, 2016 (Mw 6.0). The red traces are the vertical, north-south and east-west components of Trillium 240 s sensor (GIGS) and the black trace is the water pressure signal (arbitrary scale: velocity for the red traces and pressure for the black one). Time scale starts from 01:36:30 (UT).*

Finally, in Figure 6 we show Mw vs distance (km) for the 12 earthquakes unambiguously recorded and an estimation of the detection level of our setup. Figure 6 also includes all unobserved events (green crosses) below and near our detection level.

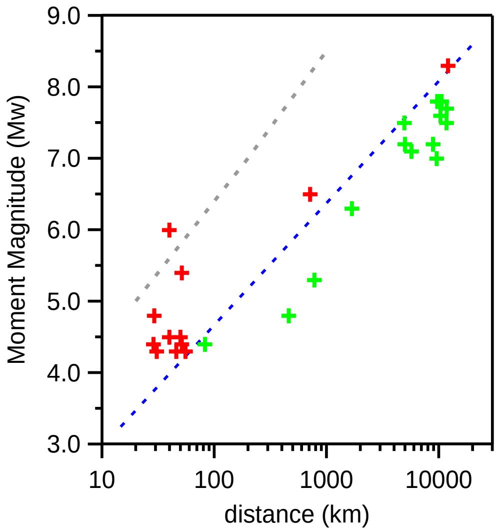

Figure 6*: Mw vs distance (km) of the 12 earthquakes collected by pressure sensor at S13 borehole from May 2015 to September 2016; the blue dashed line is an estimation of the detection level, while the grey dashed line is the detection level from Fig. 2 of Manga and Wang (2015). The green crosses represent earthquakes unobserved by the hydraulic pressure device.*

IV. CONCLUSIONS

We monitored several physical quantities from a borehole, named S13, that was bored during excavation works at the late '80 in the Gran Sasso aquifer near the deep underground INFN laboratory (LNGS). We continuously measured hydraulic pressure, temperature and electrical conductivity of groundwater with a high sampling rate (from 10 Hz to 50 Hz). Through the S13 monitoring, we recorded at a very high frequency into a very deep carbonate aquifer the first observations of near- and far-field earthquake signals and the related hydroseismographs (Figs. 4 and 5). Whereas, Manga and Wang (2015) provided a review of water table changes during teleseismic arrivals in wells located only in shallow aquifers. We collected clear recordings of 12 earthquakes allowing us to estimate the detection level of the hydraulic pressure device, which we foresee to be sensitive to local earthquakes (distance less of 10 km) with magnitude larger than 2.0-3.0 Mw. In Figure 6, the green crosses represent earthquakes unobserved by the hydraulic pressure device.

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