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NON-DOUBLE-COUPLE COMPONENT ANALYSIS OF INDUCED MICROEARTHQUAKES IN THE VAL D'AGRI BASIN (ITALY)

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ABSTRACT

In recent years it has become accepted that earthquake source can attain significant Non-Double-Couple (NDC) components. Among the driving factors of deviation from normal double-couple (DC) mechanisms there are the opening/closing of fracture networks and the activation of pre-existing faults by pore fluid pressure perturbations. This observation makes the thorough analysis of source mechanism of key importance for the understanding of seismicity induced by withdrawal/injection of fluids (i.e. geothermal and hydrocarbon reservoirs), and by water impoundments. The NDC components can be decomposed into isotropic (ISO) and compensated linear vector dipole (CLVD) components. In this study we investigate the full seismic moment tensor of induced microseismicity recorded in the Val d'Agri basin (Southern Apennines, Italy) focusing our attention on the NDC component. Swarm type shallow seismicity is induced by a high rate wastewater disposal well of the giant Val d'Agri oilfield (the largest in onshore Europe) and by an artificial lake characterized by severe seasonal level oscillations. Preliminary results reveal a significant NDC component for most earthquakes.

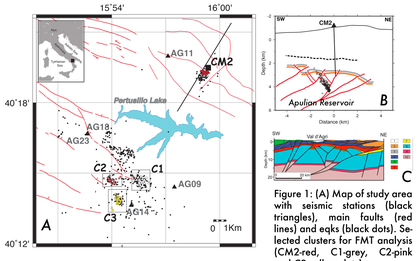


Figure 1: (A) Map of study area with seismic stations (black triangles), main faults (red lines) and eqks (black dots). Selected clusters for FMT analysis (CM2-red, C1-grey, C2-pink and C3-yellow dots).

(B) Structural section tied to CM2 well, (C) Schematic geologic section across the VDA basin (modified after Mazzoli et al. [2013]). 1 – Quaternary deposits; 2 – Flysch sediments of satellite basins (Mio-Pliocene); 3 – Pelagic successions (Cretaceous-Miocene); 4 – Mesozoic basinal rocks; 5 – Western Carbonate Platform (Mesozoic); 6 - Tectonic mélange (Miocene - Lower Pliocene); 7 - Foredeep deposits of the IAP (Pliocene); 8 - IAP reservoir (Mesozoic – Miocene); 9 - Permo-Triassic clastic deposits; 10 - Paleozoic crystal-

TECTONIC SETTING & VAL D'AGRI OILFIELD

The Val d'Agri (VDA) is a Quaternary extensional basin located in the Southern Apennines (Italy) range characterized by a complex tectonic evolution (Fig. 1). The upper crust is constituted by a stack of rootless nappes overthrusting the Inner Apulia Platform (IAP) thrust-and-fold system as a result of two main tectonic phases. NW-SE trending Quaternary normal faults cross-cut the Mio-Pliocene thrust-and-fold system and bound the VDA basin (details in the schematic geologic section in Fig. 1C). Structural data and stress indicators delineate a quite homogeneous local stress field, consistent with a regional SW–NE extension. The high seismic hazard of the area is testified by large historical earthquakes (i.e. Me 7), whereas instrumental seismicity is characterized by low-magnitude (M<3) swarms and sparse events. VDA hosts the largest oilfield in onshore Europe that produces, since the late 1990s, oil and associated gas from low-porosity Cretaceous limestones of the IAP. High-productivity is due to fracture systems at various scales. Wastewater associated to hydrocarbon production is reinjected into the Costa Molina 2 high-rate well (CM2; Fig. 1 A,B) into an unproductive marginal portion of the carbonate reservoir at 2890-3096 m depth (b.s.l.). Wastewater has been reinjected since 1 June 2006 with variable injection rate and well-head pressure reaching maximum values of 2800–3000m3/d and 13–14MPa, respectively. Disposal activity induced swarm microseismicity (ML<2) since the first injection tests. Injection induced seismicity (IIS) illuminates an inherited reverse fault confined within the IAP (Fig.1B) and earthquake rate strongly correlates with well-head injection pressure (Improta et al., 2015). A water reservoir (Pertusillo Lake impoundment, 75 km2 and 140 Mm3) is located in the southern portion of the VDA. Protracted Reservoir Induced Seismicity (RIS) (ML<3) has been observed since 2001 at 2-5 km depth within the IAP and related to severe seasonal variation in the reservoir storage (e.g. 80 Mm3). This seismicity is interpreted as induced by pore fluid pressure diffusion within the fractured IAP (Valoroso et al., 2009).

DATA & METHODOLOGY

The data-set includes swarm-type microseismicity recorded between 2005-2006 by a high-performance local network run by INGV (Mc 0.4, 23 stations) and accurately located by high-resolution local earthquake tomography. We separately analyzed two different clusters seismicity: (1) the CM2-linked IIS, a swarm of 69 earthquakes with 0.3 ≤ ML ≤ 1.8 occurred during the initial daily injection tests (2-12 June 2006); (2) the RIS linked to Pertusillo lake which includes 526 earthquakes with -0.2 ≤ ML ≤ 2.7. To perform full moment tensor (FMT) analysis we use the HybridMT technique (Andersen, 2001; Kwiatek et al., 2016). After a selection based on signal-to-noise ratio, we filter (2-50 Hz) the seismograms and estimate P-wave pulse polarities and areas for 35 (CM2) and 82 (Pertusillo) events. These latter ones were divided into 3 different spatial clusters (C1, C2, C3; Fig.1A). After FMT inversion, we finally achieved very stable results for the following selected events: 30 (CM2; ML ≥ 0.5), 28 (C1), 18 (C2) and 30 (C3) events with ML ≥ 0.6 for both single and cluster inversions, respectively (Fig.1A). Uncertainties of estimated MTs are expressed by normalized root-mean-square (RMS errors) between theoretical and estimated amplitudes (Vavricuk et al., 2014).

CM2 INJECTION WELL

For the best FMT inversions (RMS values ≤ 0.5), we produce the source type plots (Hudson et al., 1989). Though the source-type distribution is quite heterogeneous %NDC is significant for most events. Most of sources fall in %ISO- and %CLVD- zone, and only a small portion in DC and ISO+ and CLVD+ regions (Fig.2A). The constrained DC solutions obtained for single MT inversion (Fig.2B) show a representative variability of Normal Fault (NF) focal mechanisms.

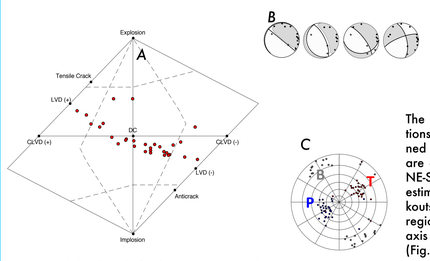


Figure 2: (A) Hudson plot for cluster inversion CM2, (B) Representative constrained DC focal mechanims, (C) polar projection of P, T and B axes.

The resulting stress orientations (Fig.2C) are well defined and directions of T axes are coherent with the local NE-SW Shmax orientation estimated by borehole breakouts. Coherently with the regional stress regime, P axis is not perfectly vertical (Fig.1B).

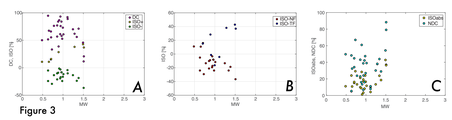


Figure 3

Figs 3 show the %NDC versus estimated MW. We observe that both %ISO+ and %ISO- tend to increase with MW (Fig. 3A). NF mechanisms prevail. %ISO+ is predominantly related to events classified as Thrust Fault (TF), the same characterized by the highest MW (Fig. 3B). Also, %NDC reaches values around 90% in correspondence to the highest MW values (Fig. 3C). In Fig.4 we plot %DC, %NDC and %ISO as a function of hypocentral distance from the wellbore. We do not find clear dependence with distance likely because seismicity is strongly clusterized within the fault zone (Fig. 1B).

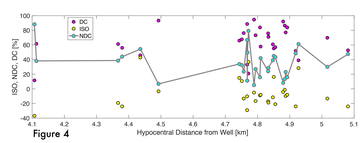


Figure 4

Figures 5 show the comparison of NDC components with hourly injection data (wellhead pressure). In Fig. 5A, %ISO+ and %CLVD+ appear (15% - 50%) only 3 days after the beginning of injection test. The few TF events (with larger %ISO+ and MW) correlate to pressure peaks. In Eqks with significant %ISO- and %CLVD- appear just after the first injection test (Fig. 5B). All sources but 2 are NF. The largest %ISO- and %CLVD- occur at high pressure levels (eqks 20, 30 and 62). In Fig.5C, we compare %NDC and %ISOabs with the pressure data. Both parameters increase with time (i.e. with injected volumes and increasing pressures). The maximum %NDC matches the highest peaks of pressure (%NDC between 70% and 90%).

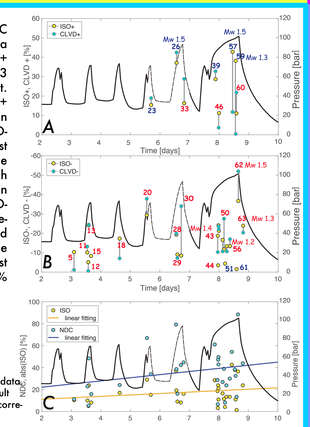


Figure 5: NDC components and injection pressure data. Eqks with normal fault (red numbers) and thrust fault (blue numbers) mechanism are indicated with the correspondent identification number.

PERTUSILLO

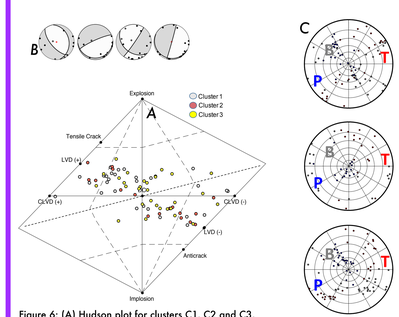


Figure 6: (A) Hudson plot for clusters C1, C2 and C3, (B) Representative constrained DC focal mechanims, (C) polar projection of P, T and B axes.

From the best FMT inversions executed for each cluster separately (RMS values ≤ 0.7), we obtain the source type plots (Hudson et al., 1989) for the different clusters seismicity (C1, C2 and C3 in Fig.1A). %NDC is significant for most events that show some not homogenous source distributions: clusterized for %ISO+ and %CLVD+ and scattered for %DC, %ISO- and %CLVD- (Fig.6A). The constrained DC solutions obtained for single MT inversion (Fig.6B) show a representative variability of NF and Strike-Slip (SS) focal mechanisms. The resulting stress orientations (Fig.6C) are not well defined.

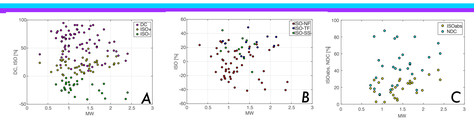


Figure 7

Figs 7 show the %NDC versus estimated MW. Both %ISO+ and %ISO- tend to increase with MW (Fig.7A). The events are classified as NF, TF and SS. %ISO+ is almost completely related to TF events. The highest %ISO- attain to NF events (Fig.7B). No relations with MW for %NDC, instead, %ISOabs increase with MW. Fig. 8 shows %NDC and %ISOabs versus the hypocentral distance from the Pertusillo Lake. We observe a slight decrease of %NDC and %ISOabs from the closest (C1) to the farthest (C3) cluster, as expected.

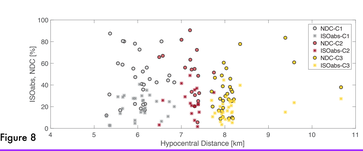


Figure 8

Figs 9 show %NDC and %ISOabs compared to the seasonal water level variation of the Pertusillo Lake (A, B and C for clusters C1, C2, and C3, respectively). We do not find a clear relation between FMT solutions and the water level. But, analyzed events concentrate during high level stages. Futher analysis carried on an extented dataset are required to sample the central low level stage.

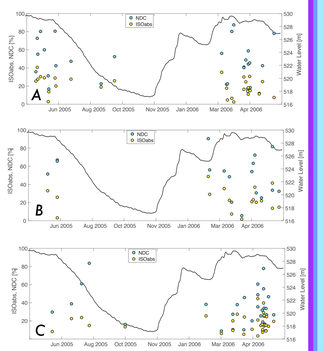
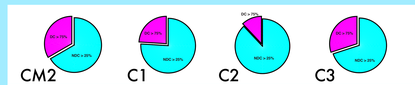


Figure 9

CONCLUSIONS



1. Both IIS and RIS show a significant %NDC component. The events with % NDC > 25% are 66% for IIS seismicity and range from 70% to 88% for the three clusters of RIS seismicity.

2. Normal-faulting regime prevails, but reverse-faulting are also present for both IIS and RIS. Most reverse-faulting events have %ISO+.

3. %NDC tend to increase with MW for IIS.

4. %ISO- and %ISO+ tend to increase with Mw for both IIS and RIS.

5. %NDC for IIS tend to increase with time (e.g. following the injection tests performed at higher rate and pressure).

6. IIS with largest %NDC are observed in correspondence of peaks in injection pressure.

7. Source mechanism of IIS is clearly controlled by injection operations (i.e. opening/closure of fractures by pressure pulses). Local stress rotation caused by pore-pressure perturbations?

8. NDC components do not correlate with seasonal variation of the lake level. But results are preliminary and further analysis will be performed using an extended eqk catalogue.

REFERENCES: Andersen L.M. (2001), A Relative Moment Tensor Inversion Tecnique applied to seismicity induced by mining; Hudson et al. (JGR, 1989), Source type plot for inversion of the moment tensor; Improta et al. (GRL, 2015), A detailed analysis of wastewater-induced seismicity in the Val d'Agri oil field (Italy); Kwiatek et al. (SRL, 2016), HybridMT a Matlab/Shell environment packeage for seismic moment tensor inversion and refinement;Valoroso et al. (GJI, 2009), Active faults and indced seismicity in the Val D'Agri area (Southern Apennines, Italy); Vavrycuc et al. (JS, 2014), Moment tensor decomposition revisited.