Available online http://amq.aiqua.it
ISSN (print): 2279-7327, ISSN (online): 2279-7335

Alpine and Mediterranean Quaternary, 33 (2), 2020, 149-156 https://doi.org/10.26382/AMQ.2020.06

EARTHQUAKE LOCATIONS AND THEIR INTERPRETATION: BRIDGING THE GAP BETWEEN SEISMOLOGICAL DATA AND GEOLOGICAL PHENOMENA.

Alfio Viganò [1], Davide Scafidi [2]

[1] Servizio Geologico, Provincia Autonoma di Trento, Trento, Italy.
[2] Dipartimento di Scienze della Terra, dell'Ambiente e della Vita, Università degli Studi di Genova, Genova, Italy.

Corresponding author: A. Viganò <alfio.vigano@provincia.tn.it>

ABSTRACT: A methodological view on earthquake locations and their geological interpretation is presented. Seismicity is considered a potential trigger and/or predisposing factor for different geological phenomena, like landslides or surface deformation and ruptures. Assuming a physical based model of earthquake nucleation, which in turn is supported by the observation of exhumed faults, earthquake locations from seismicity datasets need to be as much as possible reliable (i.e., precise and accurate) and complete. Application examples on seismicity distributions and other natural/anthropic events for the central-eastern Alps (NE Italy) clarify some critical points of numerical calculations and suggest a critical approach for appropriate data interpretation.

Keywords: Earthquakes, seismic catalogues, data reliability, landslides, Southern Alps.

1. INTRODUCTION

Earthquakes are the certain evidence of present-day deformation of the lithosphere and part of the energy they release, called radiated energy, reaches the Earth's surface in the form of seismic waves (e.g., Kanamori & Rivera, 2006). This energy quote is responsible for ground shaking and a variety of geological phenomena, such as surface deformation and rupture, rock damaging, landslide triggering, as well as impacts on people and infrastructures (e.g., Keefer, 1984; Boncio et al., 2010; Gischig et al., 2016; Ivy-Ochs et al., 2017). In particular, seismic waves can both trigger, as co-seismic causes, or affect, in the sense of predisposing factors, different types of phenomena (e.g., Boncio et al., 2010; Gischig et al., 2016; Ivy-Ochs et al., 2017). For this reason, earthquake catalogues and reliable seismicity databases (e.g., Chiarabba et al., 2015; Viganò et al., 2015; Bressan et al., 2016; Guidoboni et al., 2018; Rovida et al., 2019) are extensively used as reference data to study and interpret these geological phenomena and other seismotectonic features (e.g., Livio et al., 2014; Lu et al., 2017; Avital et al., 2018).

Regarding seismicity datasets, earthquake locations are the crucial information. In fact, the reliable estimation of hypocentral solutions is needed to accurately estimate magnitudes (e.g., Bormann, 2012), calculate focal mechanisms (e.g., Viganò et al., 2008; Reiter et al., 2019) and evaluate all the parameters related to hypocentral distance and seismic-ray tracing (attenuation and tomography; e.g., Morasca et al., 2010; Viganò et al., 2013). This is valid not only for instrumental but also historical catalogues, which permit to significantly extend the temporal range under consideration (Guidoboni et al., 2018; Rovida et al., 2019). For this reason, end-users should be completely aware of limits and strengths of earthquake catalogues, paying attention to the assumptions given during their creation and the constraints often made explicit by the authors themselves (see discussion in Wells & Coppersmith, 1994).
Here we present a methodological discussion on earthquake locations from seismicity catalogues and their common use for geological interpretation. We propose specific points, as a sort of minimum baggage of knowledge for non-seismologists, and we discuss some commonly accepted approaches and procedures to highlight their possible critical points. An introductory conceptual description of the earthquake source, together with some application examples about the Trentino region (NE Italy) are also presented.

2. EARTHQUAKE PHYSICS

Earthquake nucleation directly deals with rock mechanics and shear/tensile failure (e.g., Scholz, 2002; Vavryčuk, 2011). Dynamic instabilities (i.e., related to non-stable conditions in a state where acting forces are known) generate earthquakes both in the brittle (i.e., upper lithosphere) and ductile fields, because shocks are the result not only of brittle failure but also of plastic instabilities or catastrophic phase changes (Ranalli, 1995). For example, self-localizing thermal runaway has been proposed to justify intermediate-depth earthquakes (John et al., 2009). This points to the fact that «The critical stress (yield strength) and the mode of failure are functions of intrinsic and extrinsic rheological parameters» (Ranalli, 1995, p. 90), where rheology means deformation and flow of matter. Intrinsic parameters are

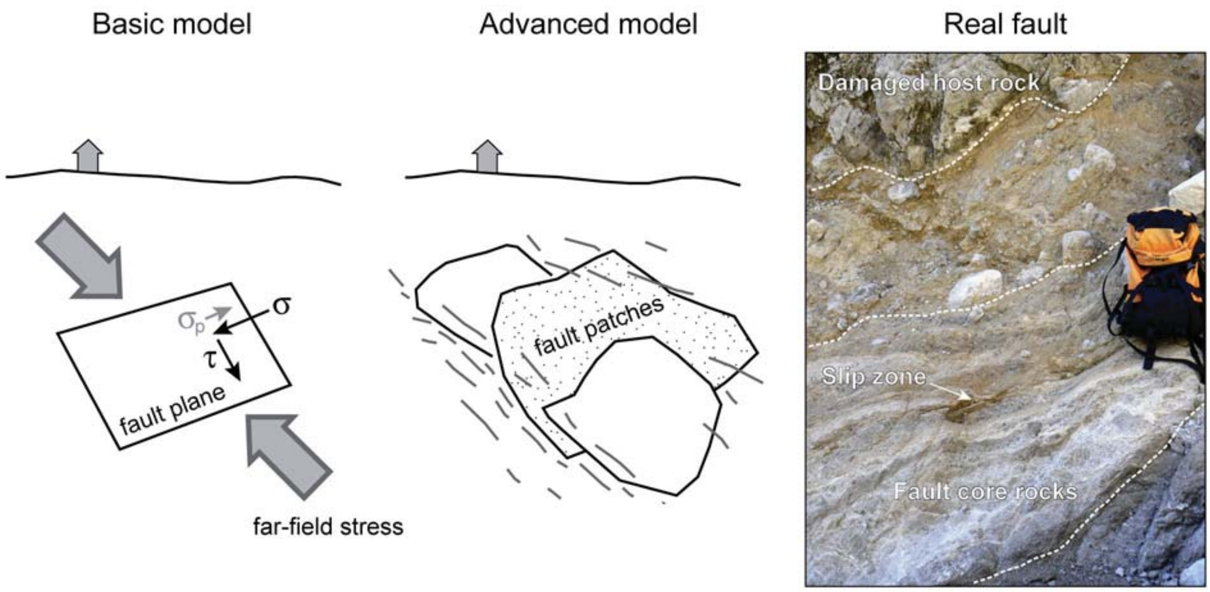

Fig. 1 - Fault models with different degree of conceptual complexity. In the basic model, the fault is a planar surface where stresses acting on the fault plane (σ, normal stress; τ, shear stress) and pore fluid pressures inside the fault (σ_p) are responsible for the seismic rupture. A more advanced model considers contiguous rupture patches, together with lateral splay faults and cataclastic bands (Scholz, 2002). In the real case (Canalone Porta fault in carbonates; Viganò et al., 2011), a complex structure (slip zone, fault core, damage zone; Sibson, 2003) and different types of rocks can be observed (cataclasites and pseudotachylytes).

related to the property of the body (i.e., rock) and thus called material parameters, such as rigidity, compressibility, viscosity. On the contrary, extrinsic parameters are temperature, pressure and time. Material parameters change at varying extrinsic conditions.

Seismicity is strongly dependent on the thermo-rheological behaviour of rocks and is critically conditioned by extrinsic rheological parameters. For this reason, a great effort is made to estimate the temperature distribution along depth within the lithosphere (e.g., Viganò et al., 2012). This means that thermo-rheological boundaries, intended as delimiting volumes of different intrinsic and/or extrinsic parameters, are important drivers for deformation and earthquake nucleation. A "fault" is not, or at least not only, simply a sliding plane with dislocated blocks (basic model in Figure 1), but the rock volume where acting forces govern the existence of dynamic instabilities as a function of rheological parameters, which in turn could significantly vary in space and time. Within this conceptual framework, seismicity can only partially fill planar surfaces in depth, being mostly located depending on crustal heterogeneities due to different crack density distributions (Bressan et al., 2016). Crustal heterogeneities can be accordingly interpreted as due to lithological variations and different levels of fracturing and/or presence of fluids (Viganò et al., 2013).

All the above considerations have feedback in the observation of exhumed fault. In fact, fault patches and splay faults (i.e., branch of faults) spread displacement over large volumes (advanced model in Figure 1) (e.g., Scholz, 2002; Sibson, 2003). Exhumed faults show very complex structures and are composed of different types of rocks (cataclasites, pseudotachylytes; Sibson & Toy, 2006; Viganò et al., 2011), which are the result of the mechanical and fluid flow properties of the fault zone (Smith et al., 2013) (real fault in Figure 1).

3. EARTHQUAKE LOCATION

The first goal of seismology is to locate the earthquake, that is calculate where and when the initial seismic rupture occurs within the rock volume (focus or hypocentre). Considering the existence, uniqueness and stability of solutions, this inverse problem is ill-posed (Hadamard, 1923). As usually happens in geophysics (Boaga, 2016), accepted its existence (i.e., earthquake has occurred), the solution is unstable and above all not unique. Viganò et al. (2015) showed that earthquake locations from different regional bulletins can differ significantly (several kilometres between epicentres) and therefore robust and detailed relocations are needed to constrain seismotectonic interpretations. This effect is the result of several causes. At first, station coverage, because recording stations must be in sufficient number and homogeneously distributed around the epicentral area. In seismological terms, it translates to a minimum number of available phase readings (for P- and S-waves) and to a minimum gap value (largest azimuthal separation in degrees between nearby stations as seen from the epicentre; e.g., gap <180°). Secondly, crustal (or Earth) models, because different assumptions on P- and S-wave velocities bring to relevant discrepancies between theoretical and observed phase arrivals times. The critical effect of an appropriate crustal velocity model in areas affected by strong lateral heterogeneities of seismic velocities has been presented by Viganò et al. (2015) for the Trentino region. Thirdly, calculation codes. Among all, Hypoellipse (Lahr, 1999) and NonLinLoc (Lomax et al., 2000) are used worldwide and should be

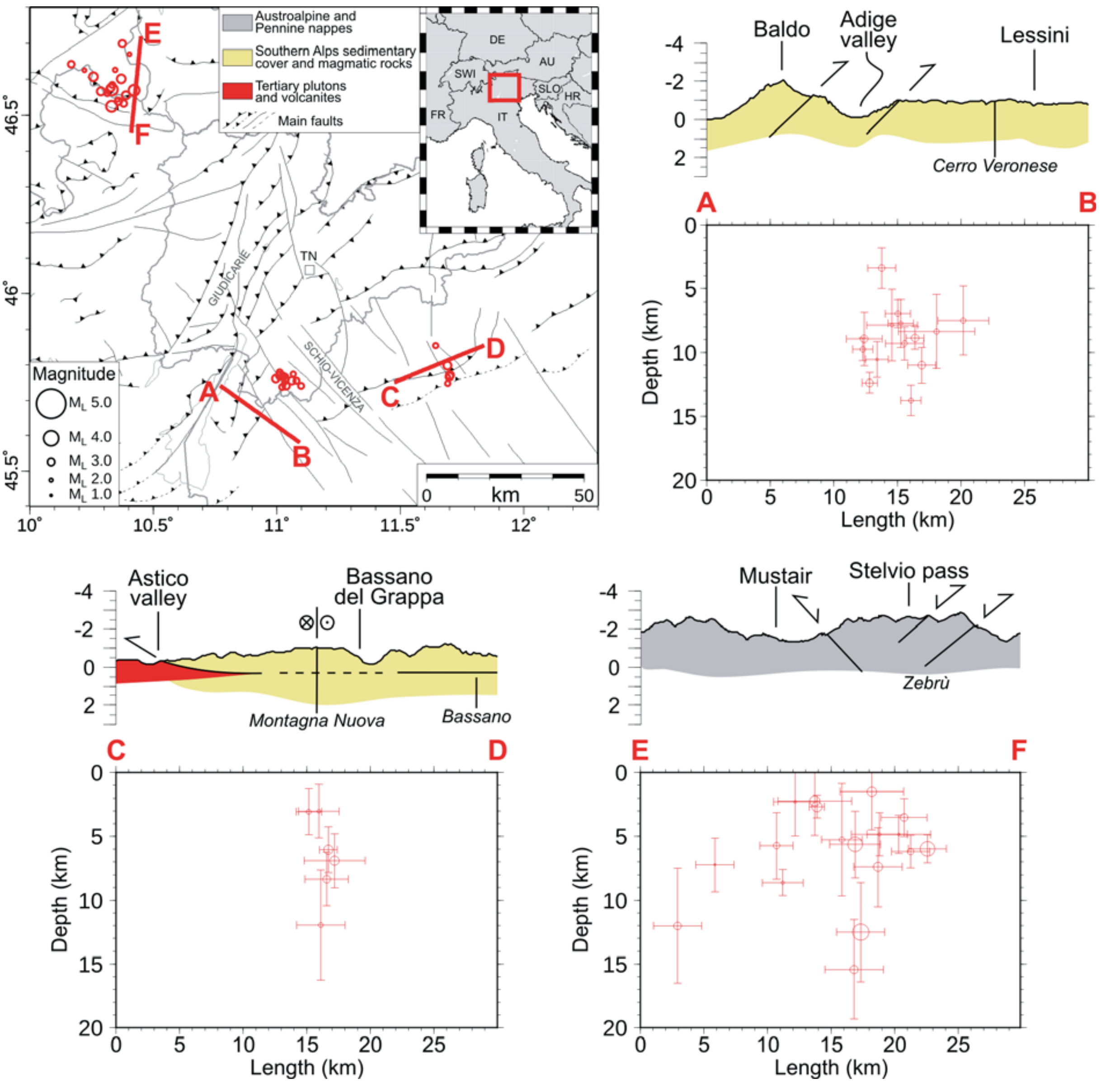

Fig. 2 - Examples of seismicity distribution, with location errors (red bars): hypocentres with small errors and not aligned (cross-section A-B), hypocentres with small errors and aligned (cross-section C-D), hypocentres with larger errors (cross-section E-F). TN, Trento.

mentioned because of the different mathematical approaches and consequent results (see discussion in Viganò et al., 2015).

Earthquake focal solutions are usually listed and grouped into seismic bulletins or earthquake catalogues. The computed hypocentral parameters include firstly the origin time, expressed as hour, minutes, seconds, and possibly hundredths of seconds, in UTC/GMT time (Coordinated Universal Time/Greenwich Mean Time). The focus is univocally located by Latitude, Longitude and depth, the last implicitly given not considering topography (positive downward, starting from 0 m a.s.l.). Magnitude, with explicit magnitude type (e.g., local magnitude M_L, duration magnitude M_D, moment magnitude M_W, etc.), completes the initial set of parameters. However, parameters describing the solution quality are also necessary. They are often expressed as spatial maximum errors in kilometres (horizontal and vertical errors, ERH and ERZ) and temporal uncertainties in seconds (Root Mean Square travel-time residual, RMS) (Bormann, 2012). Additional parameters could be the number of phases used, or total covariance if probabilistic methods are applied (Lomax et al., 2000). Particular attention should be payed when historical catalogues are examined (Guidoboni et al., 2018; Rovida et al., 2019). Since numerical models cannot be obviously applied in this case, besides origin time and epicentral coordinates the most robust information is intensity (epicentral and/or maximum) instead of magnitude. Magnitude is usually inferred from intensity using empirical formulae and expressed as equivalent magnitude based on macroseismic observations (M_e; Guidoboni et al., 2019).

4. APPLICATION EXAMPLES

In this section, some case studies about seismological data interpretation are presented. All of them concern the central-eastern Alps (NE Italy; map in Figure 2). As highlighted before, the interpretation of seismicity distribution needs a careful evaluation of location quality and errors. Figure 2 shows three cross-sections where three groups of hypocentres (data from Viganò et al., 2015) lead to different geological explanations, based on the variable level of data accuracy. In the first case, location errors are limited to a few kilometres and computed solutions at depth are very well constrained (cross section A–B of Figure 2). Despite this, hypocentres do not indicate clear alignments, suggesting the occurrence of a widespread deformation within a crustal body. As already discussed by Viganò et al. (2015), within this volume important earthquakes occur (e.g., 29 Oct 2011, M_L 4.4), which can be interpreted as due to local stress accumulation and the presence of two intersecting regional fault systems, the Giudicarie fold-and-thrust belt and the Schio-Vicenza high-angle faults. In the second case, earthquake foci are vertically aligned along the Veneto Alpine front, in optimal agreement with the Montagna Nuova strike-slip fault (cross section C–D of Figure 2). Location accuracy is the same of the first case study. Both vertical alignment and relatively small errors thus allow a complete seismological/geological interpretation. In the third case, larger horizontal and vertical errors pose a limit in the geological interpretation (cross section E–F of Figure 2). In fact, it is not possible to undoubtedly distinguish between a volume-clustered seismicity and earthquakes filling a plane.

Figure 3 shows the effect of different computational methods in quarry shot locations, but the following considerations can be extended also to seismicity. Using 1-D simplified velocity models and the HYPOELLIPSE code (Lahr, 1999) wrong locations at depth (i.e., imprecise) are achieved, with also unreliable minimal location errors (i.e., falsely accurate). In fact, computed errors do not permit to include the true shot locations (see numerical values in Table 1). In contrast, 3-D advanced velocity models and NonLinLoc probabilistic solutions (Lomax et al., 2000) are able to correctly locate the events and, despite the larger computed errors (given by the non-optimal station coverage density), to obtain highly reliable solutions. In fact, unlike tectonic earthquakes, in this case location reliability can be directly evaluated considering the true shot locations. This application example shows that, firstly, location approaches must be fully expressed by authors in catalogues and fully understood by end-users to correctly use the given solutions. Secondly, smaller location errors do not necessarily mean better quality solutions. However, it should keep in mind

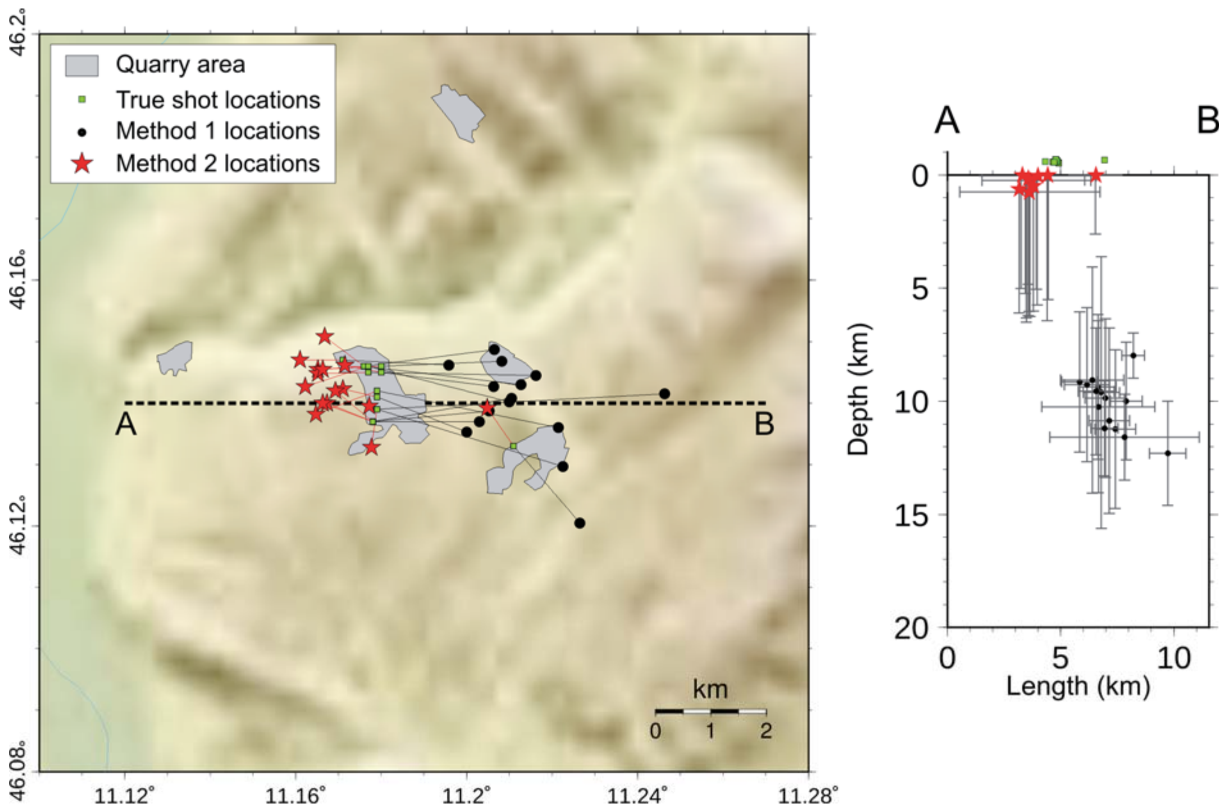

Fig. 3 - Map and cross-section of quarry shot locations (the area is about 10 kilometres NE of the city of Trento; cf. Figure 2), with solutions obtained using 1D (method 1, black dots; HYPOELLIPSE code; Lahr, 1999) and 3D velocity models (method 2, red stars; NonLinLoc code; Lomax et al., 2000). Location errors are also shown (black bars) (modified from Viganò et al., 2015).

Location	Time (yyyy-mm-dd HH:MM:SS.ss UTC)	Latitude (°N)	Longitude (°E)	Elevation (m)	ERH (m)	ERZ (m)	RMS (s)	M_L (-)
Fornace quarry shot								
Real	2013-01-25 ~15:30	46.133	11.211	790	50	10	-	-
Computed (method 1)	2013-01-25 15:25:46.77	46.121	11.227	-8000	500	1000	0.15	0.4±0.3
Computed (method 2)	2013-01-25 15:25:46.46	46.139	11.205	-10	1200	2600	0.10	0.4±0.3
Cima Undici rockfall								
Real	-	46.407	11.718	2150	100	100	-	-
Computed (method 1)	2016-07-07 05:06:22.44	46.408	11.676	-5100	7400	99000	1.81	1.9±0.3
Computed (method 2)	2016-07-07 05:06:20.66	46.405	11.693	3000	900	900	0.36	1.9±0.3

Tab. 1 - Real and computed locations for two events occurred at the Earth's surface (Fornace quarry shot and Cima Undici rockfall). "method 1" is given by HYPOELLIPSE code (Lahr, 1999) and 1-D velocity model; "method 2" is given by NonLinLoc code (Lomax et al., 2000) and 3-D velocity model. ERH, horizontal error; ERZ, vertical error; RMS, Root Mean Square; M_L, local magnitude (with computed uncertainty).

that also advanced location methods (e.g., NonLinLoc) can unreliably locate earthquakes, if not well constrained due to all the considerations given above (e.g., station coverage, velocity model).

Similar considerations can be done for the location of another type of geological phenomena at the Earth's surface. The Cima Undici rockfall, which moved about 75,000 m^3 of limestones (Scafidi et al., 2018), can be properly located only if the most reliable computational method for the area is applied (Table 1). It should be also considered that seismic recordings related to landslides significantly differ from those of tectonic earthquakes, especially in terms of frequency content and duration. In fact, landslide spectrograms (i.e., spectra of frequencies at varying time) have a typical triangular shape, higher frequencies decay more rapidly, and the main energy content is usually found within a typical 1-5 Hz range (e.g., Dammeier et al., 2011; Provost et al., 2018). Also in the Cima Undici case study, a direct comparison between real and computed solutions can be performed. In contrast, since earthquake locations are necessarily given as they are and testing of the location procedure is not always possible (cf. Viganò et al., 2015), a complete and thoughtful analysis on data must be performed previously they are used and interpreted. Moreover, a complete check of available seismological data should be done by end-users, as a function of the geological phenomena they are dealing with. As an example, for landslides, a complete magnitude calculation (i.e., together with its computed, not broadly estimated, uncertainty value) is particularly important because crucial to apply regression curves on moved mass (Manconi et al., 2016).

5. DISCUSSION AND CONCLUSIONS

The geological interpretation of seismological data is not straightforward (e.g., Barchi & Mirabella, 2009). Too simplistic interpretations can be given, considering locations without discussing their precision and accuracy. As a typical example, the use of hypocentres (or even epicentres only) to infer the existence of a fault in depth or to demonstrate the present activity of a geologically-known tectonic structure. In general, a comprehensive analysis should firstly consider seismological data already available for the study area, in order to collect information and select the adequate database (Figure 4). As a very preliminary but not obvious consideration, the number of significant digits on location parameters must be evaluated. One degree of Latitude and Longitude, for example in the Trentino region (cf. Figure 2), measure about 111 and 78 km, respectively. So, three decimal digits for Latitude and Longitude degree values mean about 0.1 km in both the cases. Since location errors for earthquakes are typically larger than 1 km, a number of significant digits greater than 3 essentially does not make sense and is severely misleading. Geological interpreters must properly consider location coordinates with errors and, consequently, plot epicentral distributions. Similar considerations on significant digits should be clearly done also for all the other solutions parameters (i.e., depth, errors themselves, etc.). As mentioned before, it should be emphasized that seismic network configuration plays a crucial role in location solutions and their quality assessment. In particular, many parameters act jointly, such as the total number of stations and their epicentral distance, azimuthal gap, and the presence of at least one recording station relatively near the epicentre (e.g., Bondár et al., 2004; Tiira et al., 2016).

Then, a possibly complete identification of the geological phenomena should be done, with also the estimation of their uncertainties on, for example, mechanisms, driving factors and age (Figure 4). This leads to the core phase, where earthquake locations are used and interpreted. Assuming in-depth analyses on data, method and solution quality (for instrumental seismicity), any interpretation must be conceptually (i.e., within the

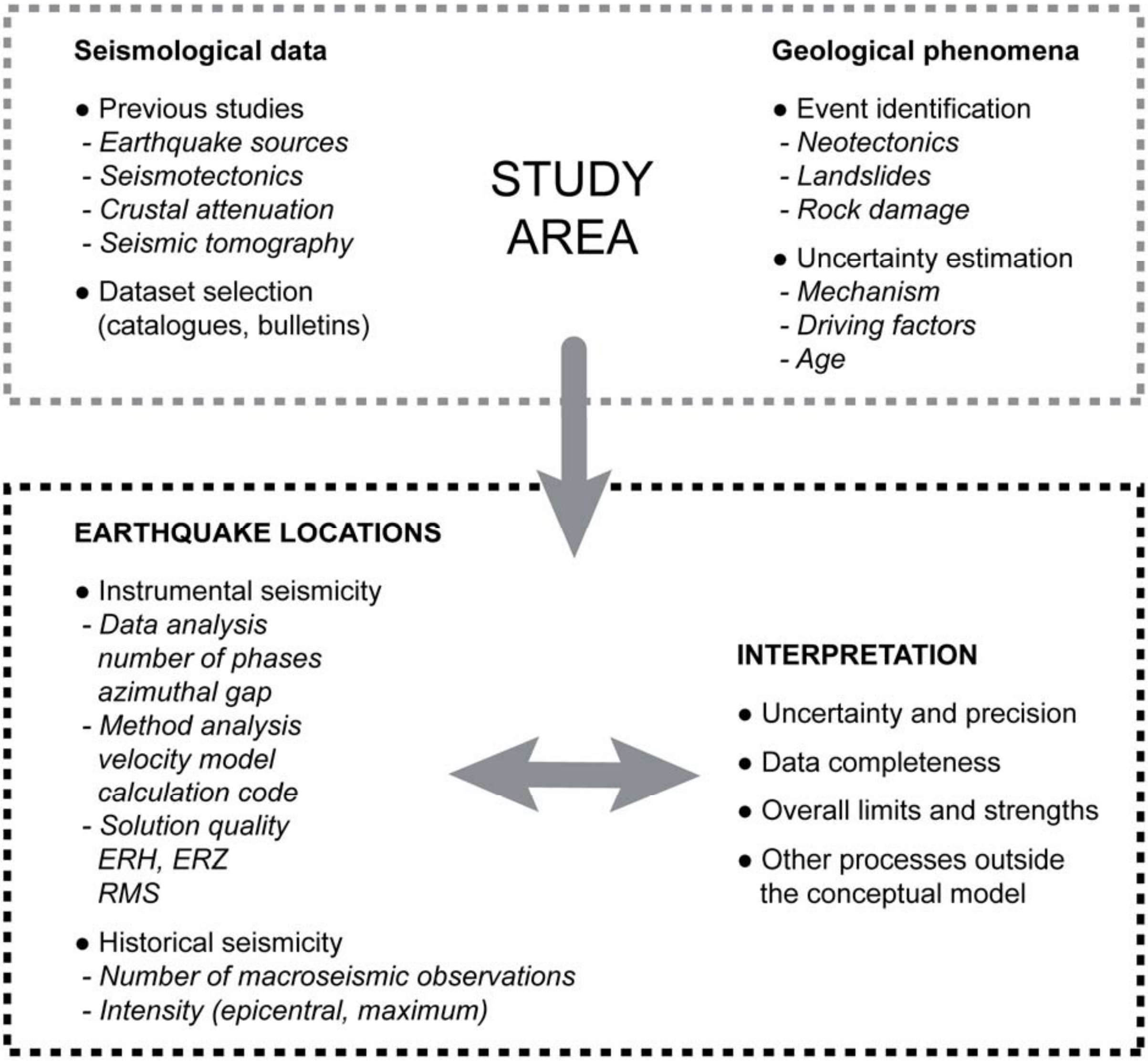

Fig. 4 - Comprehensive check-list for earthquake location data analysis and interpretation.

range of theoretical applicability) and quantitatively (i.e., within value uncertainties) consequential from seismological data. In other words, we must make sure that we do not let the data say what they cannot say.

Finally, data reliability concerns not only about precision and accuracy, but also completeness (Figure 4). As an example, if we would like to make a selection on historical seismicity for the central-eastern Alps to be compared to catastrophic landslides in this region (cf. Ivy-Ochs et al., 2017), we must consider the most complete catalogues (CFTI5Med by Guidoboni et al., 2018; CPTI15 vers. 2 by Rovida et al., 2019). If we uncritically plot epicentral coordinates from CFTI5Med and CPTI15 we obtain two different results. In the first case, we include the most relevant historical earthquake in southern Trentino (the "Middle Adige Valley" event, 1046 AD). In the second case, we completely miss it (the earthquake is listed but not completed with epicentral coordinates, due to specific choices in event selection).

In conclusions, final remarks can be summarized as follows:

- A complete and appropriate use of earthquake locations is a difficult task, because both their calculation is an ill-posed inverse problem and their geological interpretation is not straightforward.
- Rheological theory on earthquake nucleation and realistic conceptual models of faults imply a careful analysis of seismicity datasets, in terms of data, method and solution quality, to assess their overall reliability.
- A comprehensive check-list for non-seismologists is able to support data interpretation, in order to better explain geological phenomena and avoid some commonly accepted critical points.

ACKNOWLEDGEMENTS

Gianni Bressan is gratefully acknowledged for inspiring many considerations presented in this paper. We also thank J. Boaga and M. Ostermann for their helpful comments and suggestions.

REFERENCES

Avital M., Kamai R., Davis M., Dor O. (2018) - The effect of alternative seismotectonic models on PSHA results - a sensitivity study for two sites in Israel. Natural Hazards and Earth System Sciences, 18, 499-514.

Barchi M.R., Mirabella F. (2009) - The 1997-98 Umbria-Marche earthquake sequence: "Geological" vs. "seismological" faults. Tectonophysics, 476, 170-179.

Boaga J. (2016) - The ill-posed problem in geophysics. Atti del Workshop in Geofisica, 3-4 dicembre 2015, Rovereto, 3-12.

Boncio, P., Pizzi A., Brozzetti F., Pomposo G., Lavecchia G., Di Naccio D. (2010) - Coseismic ground deformation of the 6 April 2009 L'Aquila earthquake (central Italy, M_W6.3). Geophysical Research Letters, 37.
Doi: 10.1029/2010GL042807

Bondár I., Myers S.C., Engdahl E.R., Bergman E.A. (2004) - Epicentre accuracy based on seismic network criteria. Geophysical Journal International, 156, 483-496.

Bormann P. (2012) - New Manual of Seismological Observatory Practice (NMSOP-2), IASPEI. GFZ German Research Centre for Geosciences, Potsdam.
http://nmsop.gfz-potsdam.de

Bressan G., Ponton M., Rossi G., Urban S. (2016) - Spatial organization of seismicity and fracture pattern in NE Italy and W Slovenia. Journal of Seismology, 20, 511-534.

Chiarabba C., De Gori P., Mele F.M. (2015) - Recent seismicity of Italy: active tectonics of the central Mediterranean region and seismicity rate changes after the M_W 6.3 L'Aquila earthquake. Tectonophysics, 638, 82-93.

Dammeier F., Moore J.R., Haslinger F., Loew S. (2011) - Characterization of alpine rockslides using statistical analysis of seismic signals. Journal of Geophysical Research, Earth Surface, 116.
Doi: 10.1029/2011JF002037

Gischig V., Preisig G., Eberhardt E. (2016) - Numerical investigation of seismically induced rock mass fatigue as a mechanism contributing to the progressive failure of deep-seated landslides. Rock Mechanics and Rock Engineering, 49, 2457-2478.

Guidoboni E., Ferrari G., Mariotti D., Comastri A., Tarabusi G., Sgattoni G., Valensise G. (2018) - CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.-1997) e nell'area Mediterranea (760 a.C.-1500). Istituto Nazionale di Geofisica e Vulcanologia (INGV)
Doi: 10.6092/ingv.it-cfti5

Guidoboni E., Ferrari G., Tarabusi G., Sgattoni G., Comastri A., Mariotti D., Ciuccarelli C., Bianchi M. G., Valensise G. (2019) - CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area. Scientific Data, 6:80.
Doi: 10.1038/s41597-019-0091-9

Hadamard J. (1923) - Lectures on Cauchy's problem in linear partial differential equations. Dover Phoenix editions. Dover Publications, New York, pp. 22.

Ivy-Ochs S., Martin S., Campedel P., Hippe K., Alfimov V., Vockenhuber C., Andreotti E., Carugati G., Pasqual D., Rigo M., Viganò A. (2017) - Geomorphology and age of the Marocche di Dro rock avalanches (Trentino, Italy). Quaternary Science Reviews, 169, 188-205.

John T., Medvedev S., Rüpke L.H., Andersen T.B., Podladchikov Y.Y., Austrheim H. (2009) - Generation of intermediate-depth earthquakes by self-localizing thermal runaway. Nature Geoscience, 2, 137-140.

Kanamori H., Rivera L. (2006) - Energy partitioning during an earthquake. In: Abercrombie R., McGarr A., Di Toro G., Kanamori H. (Eds.) Earthquakes: radiated energy and the physics of faulting. Geophysical Monograph, 170, 3-13.

Keefer D.K. (1984) - Landslides caused by earthquakes. Geological Society of America Bulletin, 95, 406-421.

Lahr J.C. (1999) - HYPOELLIPSE: a computer program for determining local earthquake hypocentral parameters, magnitude, and first-motion pattern (Y2K compliant version). U.S.G.S. Open File Report 99-23, pp. 116.

Livio F.A., Berlusconi A., Zerboni A., Trombino L., Sileo G., Michetti A.M., Rodnight H., Spötl C. (2014) - Progressive offset and surface deformation along a seismogenic blind thrust in the Po plain foredeep (Southern Alps, Northern Italy). Journal of Geophysical Research, Solid Earth, 119, 7701-7721.

Lomax A., Virieux J., Volant P., Berge-Thierry C. (2000) - Probabilistic earthquake location in 3D and layered models: introduction of a Metropolis–Gibbs method and comparison with linear locations. In: Thurber C. H., Rabinowitz N. (Eds.) Advances in seismic event location. Kluwer, Amsterdam, 101-134.

Lu Y., Waldmann N., Alsop G.I., Marco S. (2017) - Interpreting soft sediment deformation and mass transport deposits as seismites in the Dead Sea depocenter. Journal of Geophysical Research, Solid Earth, 122, 8305-8325.

Manconi A., Picozzi M., Coviello V., De Santis F., Elia L. (2016) - Real-time detection, location, and characterization of rockslides using broadband regional seismic networks. Geophysical Research Letters, 43, 6960-6967.

Morasca P., Massa M., Laprocina E., Mayeda K., Phillips S., Malagnini L., Spallarossa D., Costa G., Augliera P. (2010) - Improved 2-D attenuation analysis for Northern Italy using a merged dataset from selected regional seismic networks. Journal of Seismology, 14, 727-738.

Provost F., Malet J.-P., Hibert C., Helmstetter A., Radiguet M., Amitrano D., Langet N., Larose E., Abancó C., Hürlimann M., Lebourg T., Levy C., Le

Roy G., Ulrich P., Vidal M., Vial B. (2018) - Towards a standard typology of endogenous landslide seismic sources. Earth Surface Dynamics, 6, 1059-1088.
Ranalli G. (1995) - Rheology of the Earth. second ed. Chapman & Hall, London, pp. 413.
Reiter F., Freudenthaler C., Hausmann H., Ortner H., Lenhardt W., Brandner R. (2019) - Active seismotectonic deformation in front of the Dolomites indenter, Eastern Alps. Tectonics, 37, 4625-4654.
Rovida A., Locati M., Camassi R., Lolli B., Gasperini P. (2019) - Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 2.0. Istituto Nazionale di Geofisica e Vulcanologia (INGV).
Doi: 10.13127/CPTI/CPTI15.2
Scafidi D., Viganò A., Ferretti G., Spallarossa D. (2018) - Robust picking and accurate location with RSNI-Picker$_2$: real-time automatic monitoring of earthquakes and nontectonic events. Seismological Research Letters, 89, 1478-1487.
Scholz C.H. (2002) - The mechanics of earthquake and faulting. second ed. Cambridge University Press, pp. 471.
Sibson R.H. (2003) - Thickness of the seismic slip zone. Bulletin of the Seismological Society of America, 93, 1169-1178.
Sibson R.H., Toy V.G. (2006) - The habitat of fault-generated pseudotachylyte: presence vs. absence of friction-melt. In: Abercrombie R., McGarr A., Di Toro G., Kanamori H. (Eds.) Earthquakes: radiated energy and the physics of faulting. Geophysical Monograph, 170, 153-166.
Smith S.A.F., Bistacchi A., Mitchell T.M., Mittempergher S., Di Toro G. (2013) - The structure of an exhumed intraplate seismogenic fault in crystalline basement. Tectonophysics, 599, 29-44.
Tiira T., Uski M., Kortström J., Kaisko O., Korja A. (2016) - Local seismic network for monitoring of a potential nuclear power plant area. Journal of Seismology, 20, 397-417.
Vavryčuk V. (2011) - Tensile earthquakes: theory, modeling, and inversion. Journal of Geophysical Research, Solid Earth, 116.
Doi: 10.1029/2011JB008770
Viganò A., Bressan G., Ranalli G., Martin S. (2008) - Focal mechanism inversion in the Giudicarie–Lessini seismotectonic region (Southern Alps, Italy): insights on tectonic stress and strain. Tectonophysics, 460, 106-115.
Viganò A., Tumiati S., Recchia S., Martin S., Marelli M., Rigon R. (2011) - Carbonate pseudotachylytes: evidence for seismic faulting along carbonate faults. Terra Nova, 23, 187-194.
Viganò A., Della Vedova B., Ranalli G., Martin S., Scafidi D. (2012) - Geothermal and rheological regime in the Po plain sector of Adria (Northern Italy). Italian Journal of Geosciences, 131, 228-240.
Viganò A., Scafidi D., Martin S., Spallarossa D. (2013) - Structure and properties of the Adriatic crust in the central-eastern Southern Alps (Italy) from local earthquake tomography. Terra Nova, 25, 504-512.
Viganò A., Scafidi D., Ranalli G., Martin S., Della Vedova B., Spallarossa D. (2015) - Earthquake relocations, crustal rheology, and active deformation in the central-eastern Alps (N Italy). Tectonophysics, 661, 81-98.
Wells D.L., Coppersmith K.J. (1994) - New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America, 84, 974-1002.

Ms. received: June 29, 2020 *Revised: August 10, 2020*
Accepted: August 10, 2020 *Available online: November 30, 2020*