Journal of South American Earth Sciences 80 (2017) 237–243

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Local magnitude scale for Valle Medio del Magdalena region, Colombia

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ARTICLE INFO

Article history:
Received 21 April 2017
Received in revised form
20 September 2017
Accepted 27 September 2017
Available online 29 September 2017

Keywords:
Valle Medio del Magdalena Colombia
Local magnitude scale
Crustal seismicity
Fracking

ABSTRACT

A local Magnitude (ML) scale for Valle Medio del Magdalena (VMM) region was defined by using 514 high quality earthquakes located at VMM area and inversion of 2797 amplitude values of horizontal components of 17 stations seismic broad band stations, simulated in a Wood-Anderson seismograph. The derived local magnitude scale for VMM region was: $M_L = \log(A\ ) + 1.3744{*}log(r) + 0.0014776{*}r - 2.397 + S$

Where A is the zero-to-peak amplitude in nm in horizontal components, r is the hypocentral distance in km, and S is the station correction. Higher values of ML were obtained for VMM region compared with those obtained with the current formula used for ML determination, and with California formula.

With this new scale ML values are adjusted to local conditions beneath VMM region leading to more realistic ML values. Moreover, with this new ML scale the seismicity caused by tectonic or fracking activity at VMM region can be monitored more accurately.

1. Introduction

Local magnitude (ML) is a way to measure the size of an earthquake by using maximum amplitude of S waves recorded in horizontal or vertical components of a seismometer. Richter (1935) defined the first formula of local magnitude for California (USA) by measuring amplitude values in a Wood Anderson (WA) seismograph. He stablished that an ML = 3 for an earthquake located at 100 km would record an amplitude of 1 mm in a Wood Anderson seismograph. This calibration is valid to epicentral distances up to 600 km and was the basis for many studies about local magnitude scales worldwide. IASPEI has suggested a generalized formula for any region based on the local conditions of California.

Hutton and Boore (1987) refined the original formula ML of Richter (1935) with the aim of adjusting it to smaller regions. They calibrated the ML formula to 17 km instead 100 km. In this way they obtained ML values more consistent for different regions. This implies that at 17 km ML is almost the same for all regions but different at 100 km. This scaling allowed to establish ML scales for many regions around the world (Greenhalgh and Singh, 1986; Baumbach et al., 2005; Keir et al., 2006; Stange, 2006; Miao and Langston, 2007; Havskov and Ottemöller, 2010). Although ML is an arbitrary and non-absolute parameter, it allows an approximate estimation of earthquake size. On the other hand, station correction is a very crucial aspect to determine ML due to local site effects, which can either overestimate or underestimate ML up to one order of magnitude or even more. At some regions with unknown magnitude scale and very heterogeneous local geology it is not recommended to use the standard formula of IASPEI. For this reason is important to define the local magnitude scale for each region considering its local conditions and attenuation curve.

Different studies have been done around the world about ML. In some places reported ML are not coincident between those calculated using the standard IASPEI formula and those done by international centers, leading to confusion and erroneous ML determination as it happened in the Sultanate of Oman (Hafiez et al., 2015). In other places such as in Italy ML scales are almost the same as that of California, (Gasperini, 2002; Bragato and Tento, 2005; Bobbio et al., 2009). On the other hand, ML studies are a key factor to seismic hazard assessment; Allen (2010) pointed out the importance of local ML scales instead of use standard formula for Australia, since it represents serious implications on seismic hazard for the recurrence of moderate to large magnitude earthquakes in that region. Rhoades and Dowrick (2000) analyzed the effects of ML on seismic hazard assessment addressing the importance of correct ML determination and its uncertainty to obtain reliable Guttenberg-Richter activity-rate parameter and b-value; moreover

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https://doi.org/10.1016/j.jsames.2017.09.033
0895-9811/

they pointed out the effects of ML on attenuation modeling for hazard estimates. With respect to ML scales for monitoring induced seismicity, Edwards and Douglas (2014) analyzed data set from different regions around the world with the aim at establishing a common magnitude definition for hazard assessment of enhanced geothermal systems. They established a correlation between ML and Moment magnitude (Mw).

In Colombia few studies about ML scales have been done. Rengifo and Ojeda (2004) proposed a ML scale for all Colombia but that formula is not appropriated for short distances and some regions (see later). Currently, Colombia National Seismic Network (CNSN) of Colombia Geological Survey (Servicio Geológico Colombiano, SGC) uses the Rengifo and Ojeda (2004) scale for the official report of ML. At some Colombia volcanic regions ML scales are available (Tamayo, 2011; Londoño, 2015; Londoño and Raigosa, 2016; Torres and Londoño, 2016).

Valle Medio del Magdalena (VMM) is a particular zone located in Northern Colombia, characterized by a sedimentary basin with abundant oil deposits. Different detailed geological and geophysical studies have been done in VMM due to the oil exploration interest but most of them are private and reserved studies of exploration companies not easily available for scientific community. On the other hand, regional studies about geology, tectonics, and deformation has been done which include VMM region (Etayo and Rodríguez, 1985; Taboada et al., 2000; Sarmiento et al., 2006; Cortes et al., 2005; Caballero et al., 2013; Bayona et al., 2013). VMM is a complex basin originated by several geological events. During the Jurassic it was a rift basin as a result of an extensional episode due to the separation of NW South America margin from North America block. Furtherly, during the Tertiary it turned on a foreland (Etayo and Rodríguez, 1985; Bayona et al., 2013). Evidence of such tectonic events are the local faulting systems associated with mayor faults of NW of South America.

Recently due to increasing interest in unconventional oil and gas extraction in Colombia the VMM region has become the subject of seismotectonics studies. In order to study the seismicity of VMM a portable broad band seismic network from beginning 2014 to December 2016 was installed by SGC. Recently Colombia government implemented some regulations with respect to monitoring of unconventional oil and gas extraction (Ministry of Mining and Energy, Law 90341 of March 2014); Particularly is of special interest to us the regulation dealing with the stopping of hydraulic stimulation when a local earthquake with ML $\geq$ 4 is recorded. This is critical for oil extraction companies, as they must stop their oil production, which leads to economic losses. On the other hand, under certain circumstances an earthquake with ML > 4 may cause damage to the population or infrastructure. If that earthquake is produced by hydraulic stimulation instead of tectonic activity, the situation becomes more complicated due to the population's concern for this type of practices. This is why is so important to determine the ML of an earthquake as much as precise as possible for regions where fracking is being performing.

Until now the seismic magnitude for VMM is calculated by using the Rengifo and Ojeda (2004) formula, which is a regional one for all Colombia territory without taking into account local conditions. Therefore, it is important and necessary to have a local seismic magnitude scale for that region. This research is about determination of a local magnitude scale for VMM by inverting amplitudes of horizontal components of broad band seismic stations by using a standard inversion method. With the new defined local magnitude scale more precise magnitude values are expected for VMM region. This becomes a clue factor for monitoring and hazard assessment of unconventional oil and gas extraction at VMM. This work is the first local seismological study done in that region.

2. Method and data

According to Richter (1935) the relationship of earthquake size and seismic amplitude is given by:

$$Ml = LogA(\Delta) - logA_o\ (\Delta) + S \tag{1}$$

Where, -logA_o is a distance correction, Δ is the epicentral distance (in km), Log$A$ is the amplitude zero-to-peak in a WA seismogram in nm, and S is the empirical station correction. The distance correction, $-$LogAo (Δ), was modified by Hutton and Boore (1987) according to:

$$-\log Ao = a \log (r/100) + b \log (r - 100) + 3 \tag{2}$$

Where a and b are the empirical geometrical dispersion and anelastic attenuation coefficients, respectively. r is the hypocentral distance (in km) and the constant value of 3 is the magnitude base level given by the original definition of ML by Richter. Accordingly, ML is defined as:

$$M_L = \log (A) = a \log (r/100) + b \log (r - 100) + 3 \tag{3}$$

Where A is the maximum amplitude (zero-to-peak, in mm) in the vertical or horizontal components simulated in a WA seismograph, and r, is the hypocentral distance (in km). For small regions the constant value of 100 in equation (3) can be replaced by 17, and the constant value of 3 can be replaced by 2 (Hutton and Boore, 1987; Havskov and Ottemöller, 2010).

The standard expression of IASPEI for ML is:

$$Ml = \log (A) + a \log (r) + br + c \tag{4}$$

Where A is in nm, c is the magnitude base level obtained from a and b values through the formula:

$$c = ML_{ref} - \log \left(A_{ref}\right) - a \log\left(r_{ref}\right) - br_{ref} \tag{5}$$

Where ML_{ref}, A_{ref} and r_{ref} are the magnitude, amplitude and distance of reference, respectively. For a distance r_{ref} of 100 km, $ML_{ref} = 3$, and $A_{ref} = 480$ nm. For a distance r_{ref} of 17 km, $ML_{ref} = 2$, and $A_{ref} = 480$ nm (Havskov and Ottemöller, 2010).

Nguyen et al. (2010) developed a method to invert amplitudes simulated in a WA seismograph to obtain ML values. In that method equations (1) and (2) are combined and a distance-correction function is defined as:

$$\sum_{k=1}^{m} M_k\delta_{ik} - \sum_{l=1}^{n} s_i\delta_{ij} - alog(r_{ij}/100) - b(r_{ij} - 100) = logA_{ij} + 3 \quad i,k = 1,2\ldots m; \quad j,l = 1,2\ldots n \tag{6}$$