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# SEISMOLOGY AT SCHOOL IN NEPAL: BUILDING AN OPERATIONAL LOW-COST SEISMIC NETWORK TO ESTABLISH AN EDUCATIONAL SEISMOLOGY PROGRAM

Subedi Shiba

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Faculté des géosciences et de l'environnement
Institut des sciences de la Terre

# SEISMOLOGY AT SCHOOL IN NEPAL: BUILDING AN OPERATIONAL LOW-COST SEISMIC NETWORK TO ESTABLISH AN EDUCATIONAL SEISMOLOGY PROGRAM

THÈSE DE DOCTORAT

présentée à la

Faculté des géosciences et de l'environnement
de l'Université de Lausanne

pour l'obtention du grade de

docteur en sciences de la Terre

par

**SHIBA SUBEDI**

| | | |
|---|---|---|
| Mr. György **HETÉNYI** | University of Lausanne | Thesis supervisor |
| Mr. Laurent **BOLLINGER** | CEA, France | External expert |
| Mr. John **CLINTON** | Swiss Seismological Service | External expert |
| Mrs. Anne **SAURON** | HES-SO Valais-Wallis | External expert |
| Mr. Michel **JABOYEDOFF** | University of Lausanne | Rapporteur |
| Mr. Dominique **ARLETTAZ** | University of Lausanne | Président |

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*To the memory of those who died in the 2015 Gorkha earthquake...*

# Abstract

Deep beneath Nepal, the India tectonic plate slides under the Himalayas and the Tibetan Plateau, and this has been causing devastating earthquakes throughout history, claiming lives and making significant damage. The most recent large event, the 2015 magnitude 7.8 Gorkha earthquake alone killed 9'000 people, injured 22'000, and caused 10 billion USD damage. Still, these consequences were far below that of the most likely earthquake scenario.

Geophysical and geological investigations of the orogen are important to understand its structure and dynamics, such as patterns of seismicity. Nevertheless, state-of-the-art geoscience knowledge reaches only a very small fraction of the local population, and research studies alone are insufficient to raise earthquake awareness and preparation level. To establish the missing link, educational efforts reaching a broad group of the population early in their life are strongly needed.

In this thesis I develop an educational seismology program in Nepal with a specific focus on two, connected pillars: (1) an operational low-cost seismic network in schools, (2) teaching earthquake-related topics in classrooms. This is implemented in Nepal for the first time and combines various elements of successful examples around the globe. The program started in a region extending from the 2015 epicenter towards the west, where a great earthquake is expected. Following laboratory and field tests on several types of low-cost seismometers, the Raspberry Shake 1D instrument was selected for our project because of its performance and adequacy to field conditions. In Nepal, 22 seismometers have been installed in schools, spanning the Nepal School Seismology Network which provides open data near real-time. These data are suitable for both classroom activities and earthquake monitoring.

Among the scientific research results, we constructed a detectability graph in *distance–magnitude* space. Using the local catalog magnitudes as a reference, we calibrated a new magnitude equation for Nepal, related to the epicentral distance and observed peak ground velocity, which performed well for more recent events. To reach the educational objectives, we prepared and adapted several materials to the Nepali education system, and performed various activities in each school. We also trained the teachers for their new classroom work with the sensor and towards better earthquake awareness. Since spring 2019, the seismometers in each school have been used to record local and global earthquakes, to allow 'learning-by-doing' activities, and to estimate the distance and magnitude of recent and nearby, usually felt earthquakes. Based on surveys before and after our program's start, educational activities implemented at schools seem to be effective in raising the awareness levels and in improving the preparedness for future earthquakes; however, perceptions of risk did not change. Overall, our approach was very well received, and the positive impact of the program is encouraging to continue and expand the efforts across Nepal.

# Résumé

Sous le Népal, la plaque tectonique indienne pénètre sous l'Himalaya et le Tibet, produisant des séismes dévastateurs depuis la nuit des temps, prenant des vies et faisant de dégâts significatifs. Le plus grand évènement récent, le séisme de magnitude 7.8 survenu à Gorkha en 2015 a tué à lui seul 9'000 personnes, en a blessé 22'000, et a fait 10 milliards de dollars de dégâts. Pourtant, ces conséquences ont été moins dévastatrices que celles du scénario le plus probable.
Des études géophysiques et géologiques d'une chaîne de montagne sont importantes pour comprendre sa structure et sa dynamique, comme par exemple la sismicité. Cependant, des connaissances modernes des géosciences n'atteignent qu'une très petite partie de la population locale, et des projets de recherche seuls sont insuffisants à augmenter le niveau de conscience et de préparation par rapport aux séismes. Pour établir le lien manquant, des efforts éducatifs qui touchent une grande partie de la population jeune sont cruciaux.

Dans cette thèse nous développons un programme de sismologie éducative au Népal autour de deux axes clés : (1) un réseau sismique opérationnel à bas coût dans des écoles, (2) un enseignement des sujets sismologiques en classe. Ceci est mis en œuvre au Népal pour la première fois, en combinant divers éléments d'exemples réussis à travers le monde.
Le programme a débuté dans une région s'étendant de l'épicentre du séisme de 2015 vers l'ouest, où un grand séisme est probable. À la suite de tests de plusieurs sismomètres à bas coût en laboratoire et sur le terrain, le Raspberry Shake 1D a été choisi pour sa performance et convenance aux conditions de terrain. Au Népal, 22 sismomètres ont été installés dans des écoles pour créer le Nepal School Seismology Network (réseau sismologique scolaire du Népal) qui fournit des données ouvertes presqu'en temps-réel. Ces données sont utiles à la fois pour des activités en classe et pour la surveillance des séismes.
Parmi les résultats scientifiques, nous avons construit un graphe de seuil de détection dans l'espace *distance–magnitude*. En se basant sur les magnitudes du catalogue local comme référence, nous avons calibré une nouvelle équation de magnitude pour le Népal, lié à la distance épicentrale et à la vitesse maximum du sol ; cette équation a démontré une bonne performance lors des événements ultérieurs.
Pour atteindre des objectifs éducatifs, nous avons préparé et adapté plusieurs matériels au système d'éducation népalais, et avons mené diverses activités dans chaque école. Nous avons également formé les enseignants à leurs nouvelles tâches en classe avec les capteurs sismiques, et à une meilleure prise de conscience vis-à-vis des séismes. Depuis le printemps 2019, les sismomètres ont été utilisés dans chaque école pour enregistrer des séismes locaux et globaux, pour des activités d'apprentissage par la pratique, et pour estimer la distance et la magnitude des séismes récents et proches, souvent ressentis par la population locale.

Basé sur des questionnaires conduits avant et après le début de notre programme, les activités éducatives implémentées dans les écoles paraissent efficaces en vue de l'augmentation du niveau de conscience et de l'amélioration de l'anticipation de séismes futurs ; cependant, la perception du risque n'a pas changé. Globalement, notre approche a été très bien accueillie, et l'impact positif de notre programme est encourageant pour continuer et étendre les efforts à travers le Népal.

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“*Mountains do not raise without earthquakes.*”
– Katherine MacKenett

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# Chapter 1

# Introduction

## 1.1 Background and motivation

In the domain of geosciences, bridging between scientists and citizens offers an opportunity for accessing scientific information to increase earthquake awareness for citizens while allowing broader data collection possibilities for scientists. The concept of educational seismology has been implemented for a couple of decades to engage students and society in seismology. These programs have demonstrated good results to improve scientific literacy, motivate the students in scientific research, increase their understanding of natural hazards, get them actively involved with real-world scientific data, and promote public awareness of seismic hazards and their anticipation. This thesis describes the first initiative in educational seismology in Nepal, which we adapted and implemented in this earthquake-prone Himalayan country.

As a result, this is not a classical, purely seismological thesis and also not a pamphlet to popularize science to a wide audience. Instead, my motivation is to do both seismology and education in parallel by installing suitable seismometers in schools for both monitoring and teaching. The objectives of the program are to increase the population's earthquake awareness for better preparedness by educating students and to use collected data in scientific research. The program has been successfully executed in western Nepal where people have very limited to no opportunity to learn about earthquakes, while the probability of a major event is high as no big earthquake occurred in the last 500 years.

This thesis is divided into six chapters. This introductory Chapter 1 presents the background context and the motivation for the study, including a review of similar initiatives around the globe. Whether western Nepal can host similar earthquakes as central Nepal or not is assessed through structural seismology analysis (Chapter 2). A detailed description of instrumentation selection and tests are presented in Chapter 3. The core of our educational seismology program, its outcomes as well as its impact are explained in Chapters 4 and 5. Finally, conclusions and perspectives in Chapter 6 close this thesis.

### 1.1.1 The Himalayas

The Himalayan arc (Fig. 1.1) and the Tibetan Plateau are formed as a result of the collision of the India plate with the Eurasia plate(e.g., Molnar and Tapponnier, 1975), which made that the Himalayas are well known as the highest, youngest and one of the best studied continental collision orogenic belts. The Indian and Eurasian continents were separated by the Tethys Ocean before > 50 million years, and the northward movement of the Indian plate marked the beginning of the collision between them, the closing of the former Tethys Ocean, and the formation of the Himalayan arc. The present-day convergence rate of the Indian plate relative to Eurasia is about 4 cm/year. Half of it is accommodated by shortening on the Main Himalayan Thrust (MHT), the megathrust and plate boundary fault present under/along the 2'500 km long Himalayan range (e.g., Bilham et al., 1997; Lavé and Avouac, 2001; Zheng et al., 2017). The surface expression of this shortening is the Main Frontal Thrust (MFT), which continues at depth, to about 15 km below the surface, for more than 100 km towards the North, forming the MHT (e.g., Cattin and Avouac, 2000; Elliott et al., 2016; Duputel et al., 2016).

The upper segment of the fault is locked from the surface to a down-dip end situated under the high Himalayan range, at a depth between 10 - 20 km (Bettinelli et al., 2006b). This segment ruptures partially or entirely during large or great earthquakes, and thereby propagates the strain accumulated at depth during the interseismic period towards the surface (Avouac et al., 2015). The resplendently located Himalayan range with its unparalleled altitude and complex

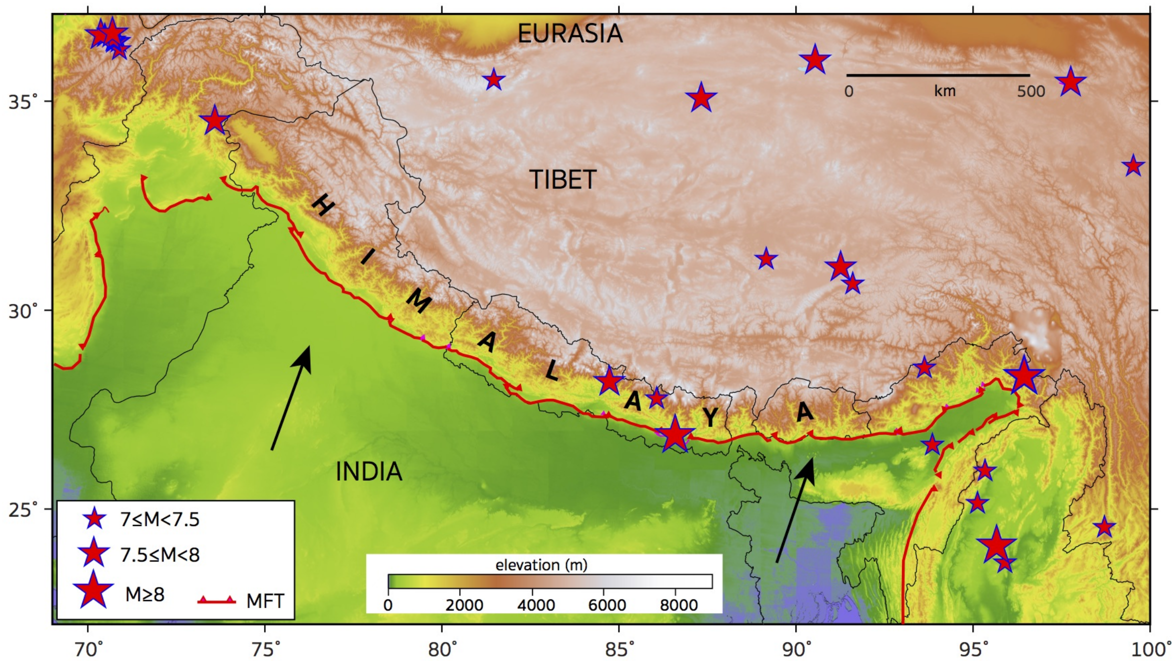


**Figure 1.1:** *$M \geq 7$ earthquakes in the Himalayas since 1934 (source: USGS). The relative motion of Indian Plate with respect to Eurasia according to GPS data is shown by black arrow (ca. 20 mm/yr).*

geological history is considered to be a perfect natural laboratory of continent–continent collision. Because of its history and complexity, the Himalayas have always been at the forefront of Earth science studies.

The Himalayan region has a long history of frequent strong earthquakes and has been shaken by great earthquakes (like the Mw 8.7 Shillong 1897; Mw 8.1 Kangra 1905; Mw 8.2 Bihar 1934; Mw 8.7 Assam 1950) in the past two centuries (Fig. 1.1) (Seeber et al., 1981). Eight earthquakes since 1600 A.D. with $M \geq 7$ are documented in the Himalaya. It is possible that the historical record is incomplete prior to 1800, but there is little reason to suppose that $M \geq 7$earthquakes are missing since then, as the reasonably good coverage of the region is given by newspapers, administrative reports and travelers' accounts in the nineteenth century. Figure 1.1 presents $M \geq 7$ earthquakes in the Himalaya since 1934.

As the Himalayas have been at the forefront of geophysical studies since long, a number of temporary seismic experiments were deployed in the past decade with denser station coverage: the HIMNT experiment (Schulte-Pelkum et al., 2005) in East Nepal and southern Tibet, the Hi-CLIMB experiment along an 800-km long profile across Central Nepal and central Tibet (Hetényi et al., 2007; Nábělek et al., 2009). These experiments succeeded to image the subsurface in the corresponding area as well as local seismicity. Recently, the Hi-KNet experiment (Hoste-Colomer et al., 2018) has been performed to study the seismicity in Western Nepal, and the structure of the crust is also studied using the same data (Subedi et al., 2018, Chapter 2).
Geophysically imaging the structure of the orogen including the geometry of MHT at depth is very important to establish quantitative models of seismic hazard (e.g., Stevens et al., 2018). Locating the seismicity both during the inter- and the post-seismic periods (e.g., Bollinger et al., 2007; Adhikari et al., 2015; Diehl et al., 2017; Hoste-Colomer et al., 2018) are equally important to understand the mechanical behavior and dynamics of the orogenic wedge. Nevertheless, state-of-the-art geoscience knowledge reaches only a very small fraction of the local population.
For example, recent publications report that there is an increased risk of a future major (M $>$ 8) earthquake in the area between west of Nepal and India (Galetzka et al., 2015; Avouac et al., 2015), and recent estimates of average return period for great earthquakes ranges from 300 to 870 years plus uncertainties (Cattin and Avouac, 2000; Bollinger et al., 2014). However, the local population is basically unaware of the presence of these findings and the related hazards.
Since no information available on when, where and how big future earthquakes will happen, better preparedness of the local communities is the only solution to reduce seismic risk. This thesis presents the importance of earthquake education for the better preparedness of the communities. This allows evaluating how one can adopt education on seismology in Nepali schools by installing inexpensive sensors. At the same time, implementation with freely available data recorded by the low-cost seismic network is presented.

### 1.1.2 Geological and tectonic setting of Nepal

Nepal lies in the central section of the Himalayan arc (Fig. 1.1) and covers a long area extending over about 800 km, starting from the Mahakali River in the west and ends at the Mechi Tista River in the east. Nepal occupies nearly one third of the mountain belt and is the home to ca. 29 million people who live in a very high seismic hazard zone. The geological investigation in the Himalaya was started during the eighteenth and early nineteenth centuries (e.g., Dhital, 2015). In Nepal, there were several studies done for the geological mapping (e.g., Hagen et al., 1961; Hagen, 1963; Hashimoto, 1973; Robinson and Martin, 2014). The great pioneers include the Swiss geologist, Toni Hagen, who over 20 years of period, contributed greatly to the early studies of Mount Everest. Nepal can be

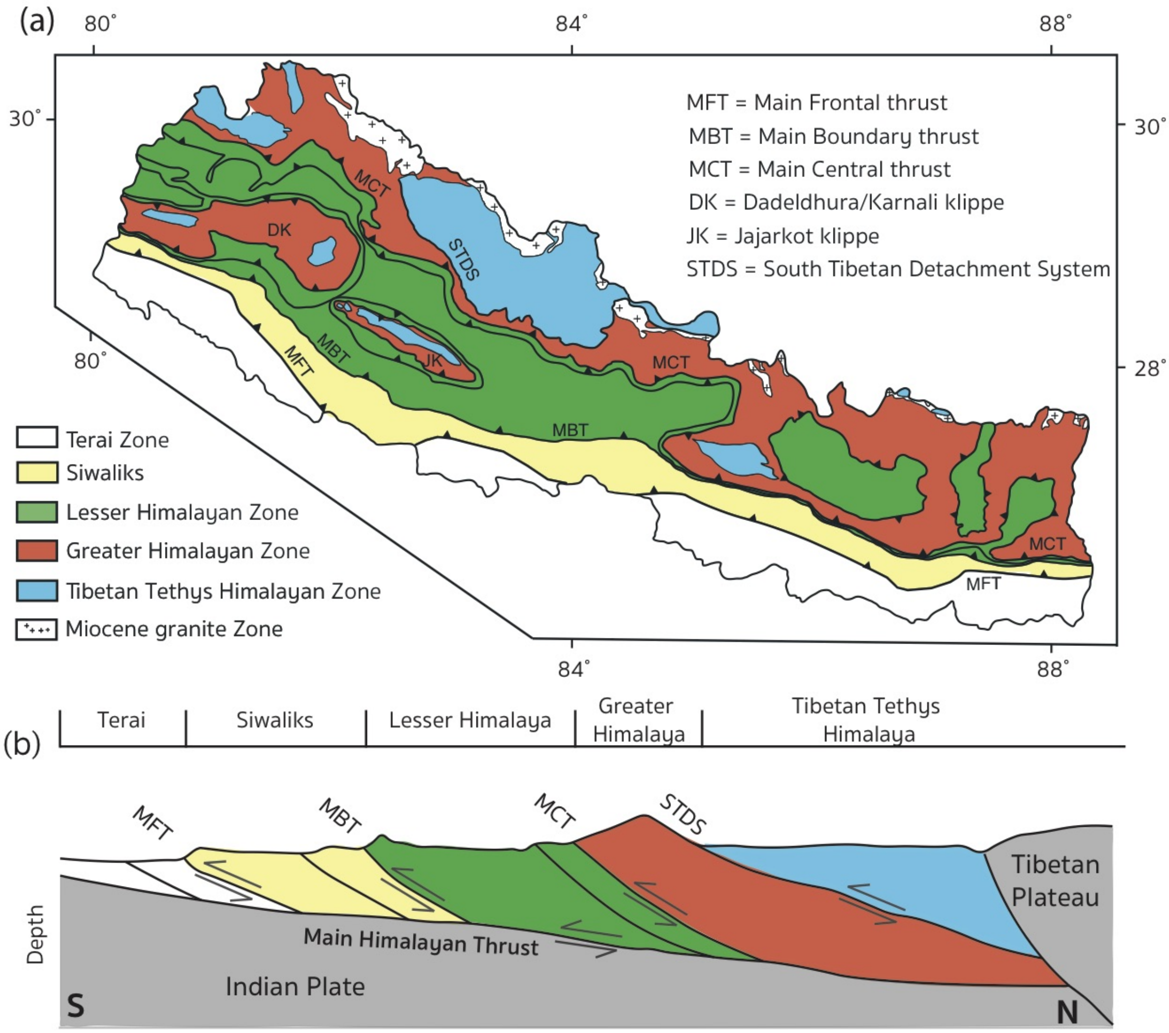


**Figure 1.2:** *(a) Geologic map of Nepal modified from Robinson and Martin (2014). Thrust faults are indicated with barbs, geological units are presented in different colors. (b) Geological cross-sections at depth modified after Harris and Whalley (2001).*

divided into 5 major geological zones, separated by major faults. Each of these zones has unique characteristics and the types of hazard as well as the underlying risk in each of them are different. The Nepal Himalayas together with the Terai belt (Fig. 1.2) is classified into the following geological zones distributed from south to north respectively (Gansser, 1964; Frank and Fuchs, 1970; Stöcklin, 1980; Dhital, 2015):

- Terai Zone
- Siwaliks
- Lesser Himalayan Zone
- Greater Himalayan Zone
- Tibetan Tethys Himalayan Zone

**Terai zone** is also called the Gangetic plain and is in the southern part of Nepal, south of the MFT. The Terai Plain is represented by Pleistocene to Holocene sediments that are not deformed by the Himalayan collision and is part of the Ganga flexural foreland basin. Its width varies from about 25 to 50 km in east Nepal to about 40 km in central Nepal, and from about 30 km in west Nepal. Its altitude fluctuates from about 100 - 200 m from east to west, respectively. This zone is at less than 200 m elevation above sea level and has a thick deposit of gravel, sand, silt and clay. It is a foreland basin that consists of the sediments brought down by the river from the northern part of Nepal. It is the Nepalese extension of the Indo-Gangetic Plains, which covers most of northern and northeastern India. It is the most densely populated part in Nepal which extends to north India.

**Siwaliks** is the zone which forms the southernmost mountain range of the Himalaya and is bounded by Main Boundary Thrust (MBT) in the north and MFT in the south. Most of the Siwalik ridges extend in the east–west direction, parallel to the Himalayan trend. Siwaliks, also known as the Sub-Himalaya zone, continues throughout the Himalaya and the Sub-Himalayan hills are easily distinguishable everywhere by the much higher mountains to their north by the abrupt difference of elevation. They, very commonly, exhibit a scarp slope to the south.

Lesser Himalayan rocks thrust southward over the Siwalik rocks along the MBT and a large part of the Siwalik Group has been buried beneath the over thrusted Lesser Himalayan rocks. This zone consists of fluvial sedimentary rocks like sandstone, mudstone, siltstone and conglomerate which are soft, loose and easily erodible. Consequently, this zone is prone to landslides.

**Lesser Himalayan Zone** is bounded by the Main Central Thrust (MCT) in the north and MBT in the south. This is the heart of Nepal composed by the attractive lowlands between the Siwaliks to the south and the high mountains to the north. Most of the densely populated valleys are located within this zone. Pokhara, Kathmandu, Panchkhal and Tumling Tar are some of the valleys in this zone. The high-grade metamorphic rocks that have traveled from the northern Higher Himalayan zone along MCT overlie the range of sedimentary, low-grade metamorphic, and crystalline rocks in this zone. Typical rock types are schists, phyllites, quartzites, limestones, dolomites. This is the area where it is marked by an increased microseismic activity. Although earthquake is a major hazard in the entire country and the corresponding shaking can cross the geological boundary, a relatively high number of earthquakes are recorded in this section.

**Greater Himalayan Zone** is bounded by the South Tibetan Detachment System (STDS), a normal fault in the north, and MCT in the south. The region is made up of metamorphic rocks and crystallines capped by sedimentary rocks with some granite intrusions. The Great Himalayan Zone stands as a barrier to the humid air coming from the Indian Ocean and prevents the moisture from entering the Tibetan Plateau, while this zone allows the passage of some deep trans-Himalayan rivers through it. These mighty rivers originate in the Tibetan marginal mountains with an altitude of less than 6'000 m, but cross a mountain range where peak altitudes exceed 8'000 m (Wager, 1933; Hagen, 1969). The south face of the Great Himalayan Zone is steeper and shorter than its north slope. The Great Himalayan zone contains a number of massifs, such as the Kanjiroba, Dhaulagiri, Annapurna, Langtang, Khumbu and Kanchenjunga. Eight summits exceeding 8'000 m elevation in Nepal also lie in this zone. Landslides due to steep slopes and glacial lake outburst floods are frequent hazards in this section.

**Tibetan Tethys Himalayan Zone** is the northernmost zone of the Nepal Himalaya and is bounded by the STDS in the south and the Indus–Tsangpo Suture Zone (ITSZ) in the north which is exposed beyond the Nepal border, inside the Tibetan Plateau. The ITSZ marks the geological boundary at the surface between southern Indian Plate rocks and northern Eurasian Plate rocks. Since there is no single continuous Great Himalaya, the intermediate areas occupied are called Inner Himalayan valleys (Hagen, 1969) and such valleys are surrounded by the Great Himalayan and Tibetan marginal zones. Tibetan Tethys Himalayan Zone constitutes the northern boundary of the Inner Himalaya. The major Himalayan rivers originating from this zone flow towards the Indian subcontinent. It consists of a sedimentary sequence known as Tibetan-Tethys Sedimentary Series that comprises of shale, sandstone, siltstone and conglomerate with competent limestone and quartzite beds. This is where famous marine sediments and fossils can be found at high elevation.

### 1.1.3 Natural hazards in Nepal

A natural hazard is an extreme event that occurs naturally and causes harm to any living creature, including humans, and properties, but usually the primary focus is on humans. The severity of the impacts from a natural hazard depends on both the physical nature of the extreme event and the details of human responses and decisions. A natural hazard mounts into a natural disaster when an extreme event causes harm in significant amount and saturates the capability of people to cope with and respond to the situation. Natural hazards tend to occur repeatedly in the same geographical regions because they are related to physical or geological characteristics of an area or weather patterns. In Nepal, earthquakes, landslides, floods are the most common natural hazards resulting in a total of 77 % of the mortalities, but the casualties from thunderstorms, cold waves, fires, avalanches are also in increasing trend in recent years (Table 1.1). This section provides a brief description of the major natural hazards in Nepal.

| **Hazard** | **Vulnerable areas** | **Total mortality** | **% of total** |
|---|---|---|---|
| Earthquake | Entire country | 9'850 | 39 |
| Landslide | Mid-mountain, mid-hills, Siwaliks | 5'148 | 20 |
| Flood | Terai, mid-hills, and valleys | 4'623 | 18 |
| Fire | Mid-hills and Terai | 1'791 | 7 |
| Lightning | Entire country | 1'787 | 7 |
| Cold wave | Mid-mountain and mid-hills | 563 | 2 |
| Others | Entire country | 1'869 | 7 |
| **Total** | | **25'631** | **100** |

**Table 1.1:** *Natural hazard, vulnerable areas and mortality in Nepal 1971 - 2018. The category 'Others' includes hazards related to high altitude, heavy rainfall, wind storm, strong wind, heat wave and avalanche. Source: MoHA (2013, 2015, 2017, 2019)*

#### 1.1.3.1 Landslides

Nepal is the country with the highest relative relief on Earth, composed of about 83 % of mountainous with often weak and fragile geological structure in a tectonically active zone. Therefore, the country is highly vulnerable to landslides, debris flows and slope failures, also because of the overgrazing of protective slope covers and high intensity rainfall during monsoon. Steep gradients and swift water flows of Himalayan rivers and streams have significantly contributed to trigger landslides every year. Only the southern border of the country, Terai (ca. 20 % of the surface area) is not vulnerable to landslides as its topography mostly consists of flat plains. Most of the landslides occur during the monsoon period in June-September, the time period which receives 80 % of the annual rainfall (Panthi et al., 2015). A total of about 20 % casualties in Nepal is reported by the landslides in the last couple of decades (Table 1.1).

In Nepal, landslides can be triggered by seismic events. In two separate studies after the Mw7.8 2015 Gorkha earthquake, more than 4'000 landslides were mapped in the week following the mainshock (Lacroix, 2016). A team from USGS reported that a few tens of thousands of landslides were triggered, and that these are distributed over an area of approximately 35'000 $km^2$, the number is later counted as > 20'000 (Valagussa et al., 2017).

Out of these landslides, a few were extremely large (250'000 $m^3$ in volume); the largest and most destructive landslide triggered by the Gorkha earthquake occurred in the Langtang valley (Collins and Jibson, 2015), where the shaking triggered a debris avalanche composed of ice, snow and soil, burying several villages, and killing at least 350 people (Kargel et al., 2016). This avalanche also dammed the river for a few days and destroyed a large part of the valley due to the air blast produced by the avalanche.

#### 1.1.3.2 Floods

As the topography of the country is steep and rugged, very high intensity of rainfall during monsoon season causes floods, in particular in Terai. There are more than 6'000 rivers and streams flowing from the northern mountainous region towards the southern Terai plains, generally with high speed due to the high river gradient. Rivers like Koshi, Gandaki, Karnali are originating from glaciers and snow-fed lakes. Moreover, intermittent rivers originating from the Siwaliks that are subject to frequent flash floods carry high sediment loads (Sharma, 1997) despite having no significant flow outside of the monsoon season. Streams and rivulets originating mostly from the Chure hills cause flash floods during monsoon rains and remain without any (or very little) flow during the dry season. In between 1971 and 2018, floods in Nepal caused 4'623 deaths (Bhandari et al., 2018), which caused 18 % of total casualties in Nepal from all natural hazards (Table 1.1). In recent years, changing precipitation patterns (MoHA, DPNet and UNDP, 2009) have increased the magnitude and frequency of floods. Flood monitoring has started in Nepal and most of the major river basins like Karnali, West Rapti, Babai, and Kankai are equipped with early warning systems. Since 2017, the Nepal government has created a new section within the Department of Hydrology and Meteorology for flood forecasting and early warning.

#### 1.1.3.3 Earthquakes

Nepal straddles the fault line between the Indian and the Eurasian plates, and the full width of the seismogenic megathrust extends beneath the country. The MHT is the fault that is able to produce the largest earthquakes and is also the main source of seismic hazard in Nepal. It is a large, shallow-dipping reverse fault and surfaces at the MFT, accommodating roughly 2 cm/yr of shortening, along which fault scarps from large past earthquakes have been found (Bollinger et al., 2014). Earthquakes are the most common and most deadly natural disaster in Nepal, claiming more than eighteen thousand lives since 1934 (MoHA, 2017). A total of more than 39 % casualties in the period 1971 - 2018 was caused by earthquakes (Table 1.1).

The occurrence of destructive great earthquakes in the past (before network installation) can be studied by historical evidence as long as records exist. As Nepal has encountered many earthquakes throughout its history, it has also records for the greatest life losses since the $12^{th}$ century. Paleo-seismological investigations along strike of the active frontal thrust confirm these events and reveal further large earthquakes. The oldest known earthquake so far, described in a primary source, has occurred in 1223, but its description remains unreadable due to defaced letters and words (Bollinger et al., 2016). It is reported that King Abhaya Malla died in the 1255 earthquake. Nine historical earthquakes (1255, 1344, 1408, 1505, 1681, 1810, 1833, 1866 and 1934) with magnitudes exceeding 7 have been documented in Nepal since 1255 (Fig. 1.3). The greatest event in Nepal, which is also the most recent great earthquake in Western Nepal, occurred in 1505, as reported in historical chronicles and corroborated through the analysis of lake sediments (Ambraseys and Jackson, 2003; Ghazoui et al., 2019). The elapsed time since then leads to the existence of a well-identified seismic gap in which another large earthquake is already due (Bollinger et al., 2016). This fits the overall view of the seismic cycle in the Himalayas, which has recorded a major earthquake all along the mountain belt in the past 500 years (Hetényi et al., 2016b).

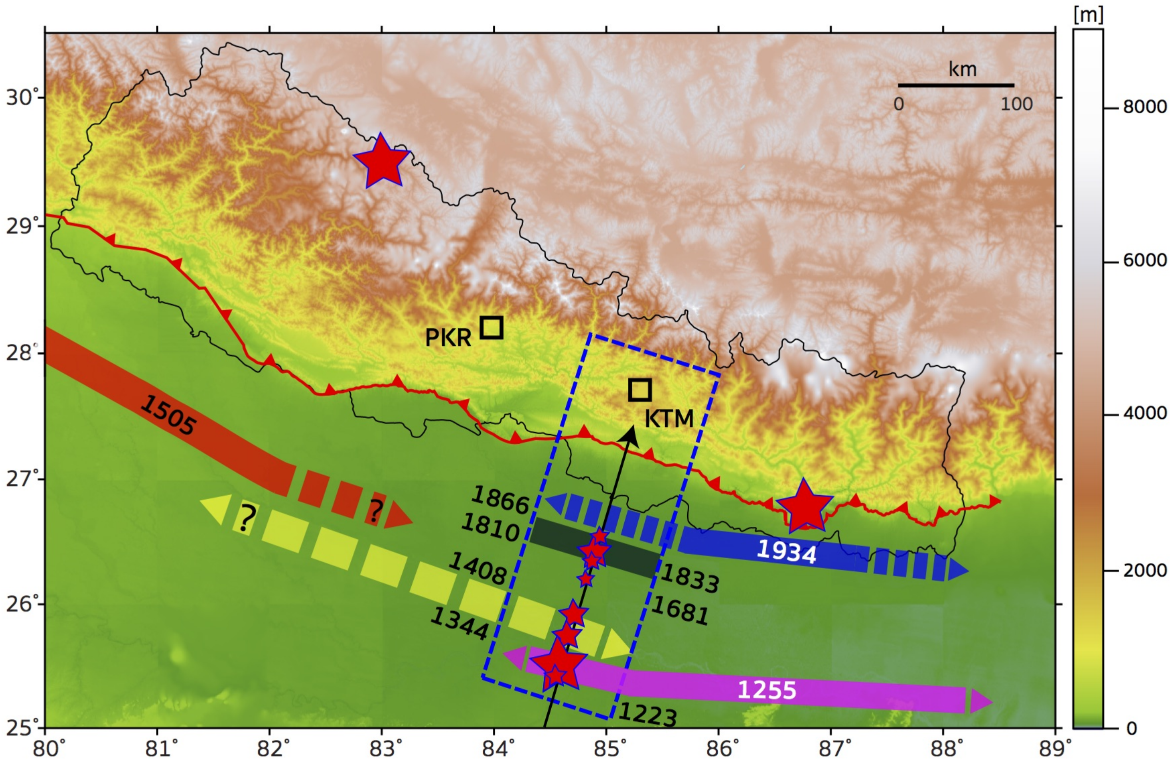


**Figure 1.3:** *Rupture lengths and return times of great Himalayan earthquakes in Nepal since 1223 to 1934, before the World-Wide Standardized Seismograph Network (WWSSN) installation. Rupture extents are consistent with limited macroseismic historical evidence and growing paleoseismological and morphotectonic data. A dashed yellow line depicts the possible 1344 or 1408 A.D. rupture trace, assuming that one of these events was a great earthquake. The MHT is denoted by a thick red line. PKR and KTM refers to Pokhara and Kathmandu, respectively. Figure modified after Bollinger et al. (2016).*

In modern seismology, microseismic monitoring is an efficient tool to understand the seismotectonics of the region and also to provide useful information to responsible authorities for post-earthquake rescue operations. Installation of the World-Wide Standardized Seismograph Network (WWSSN) has improved the capabilities of Himalayan earthquake detection

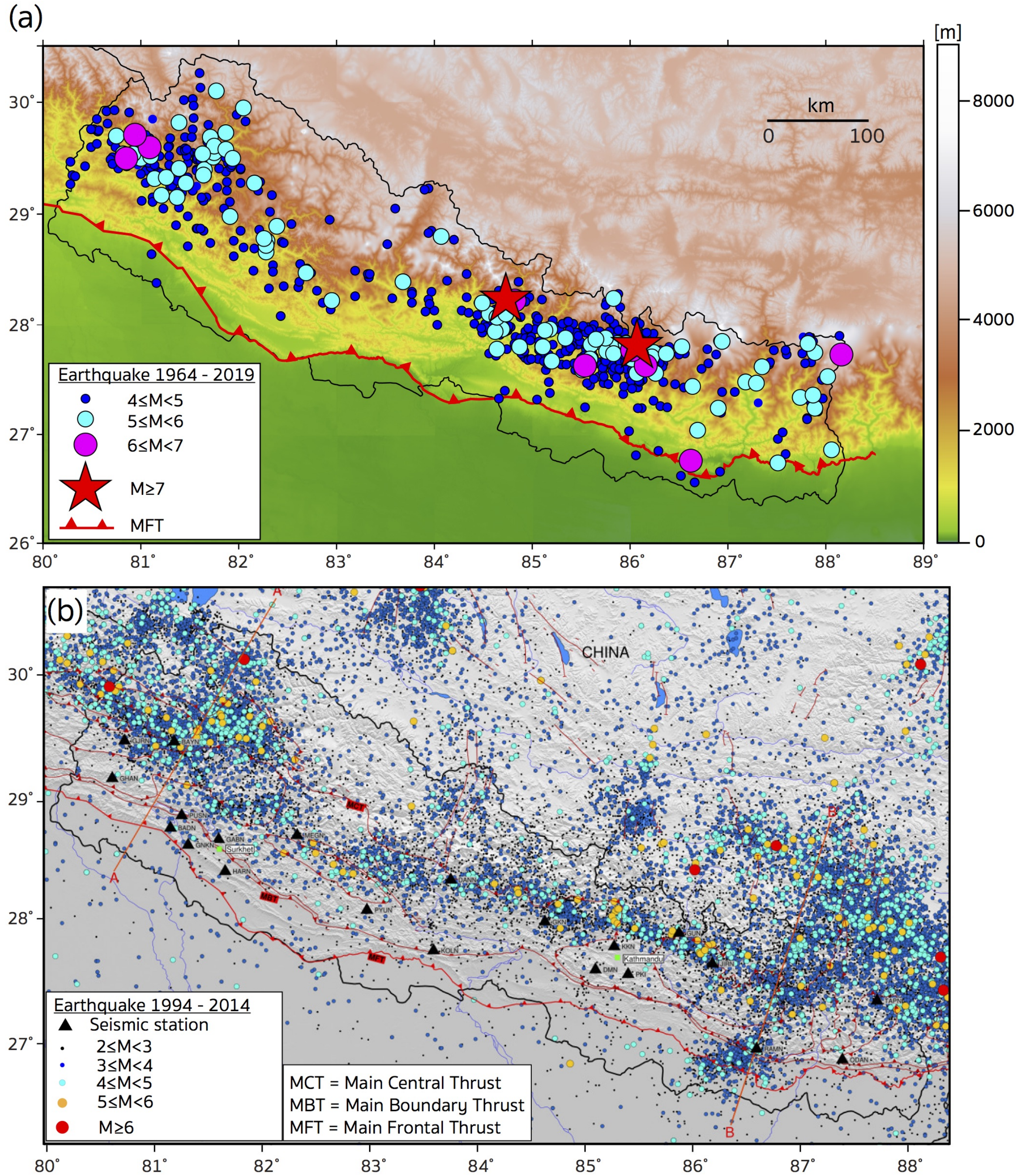


**Figure 1.4:** *(a) Seismicity map of Nepal after installation of WWSSN in 1964 - 2019 using USGS catalogue. (b) Seismicity map of Nepal and around in 1999 - 2014. Source: scanned and modified from NSC published version.*

significantly. The map of documented seismicity in Nepal before and after the installation of WWSSN is presented in Figures 1.3 and 1.4, where most of the events have been located at 10-20 km depth, which corresponds to the position of MHT below the surface (Duputel et al., 2016; Hoste-Colomer et al., 2018). In Nepal, a short period seismometer was installed south of

Kathmandu in 1978 (year 2035 B.S. in Nepali calendar). With this, microseismic monitoring in Nepal has begun by the Department of Mines and Geology (DMG), in collaboration with France.
Today, the National Seismological Centre (NSC) within DMG is running the Nepal National Network, consisting of 40 permanent seismic stations (20 short-period and 20 broadband: Lok Bijaya Adhikari, pers. comm.) all over the country where 23 (21 short-period and 2 broadband) stations were running at the time of 2015 Gorkha earthquake (Adhikari et al., 2015). In addition, to monitor the crustal shortening, NSC has installed 29 GPS stations in collaboration with Caltech, USA and DASE, France. In general, NSC provides the location and magnitude of local and regional earthquakes, on its website (for $M \geq 4$ events), to the authorities, and also to international collaborators for related seismological studies based on respective agreements. A total of 213'807 earthquakes have been recorded by NSC including the recent devastating Gorkha earthquake and aftershocks at the end of 2017 (NSC webpage).
The impact of large earthquakes on Nepal can be devastating due to high vulnerability: the poorly defined policies, low level of preparedness, and insufficient construction practices. Earthquakes threaten the entire country all the time but, although some seasonal variation of the background seismicity with more earthquakes in the winter are recorded (Bollinger et al., 2007).
In recent studies, in the aftermath of the 2015 earthquakes, it is reported that there is an increased risk of great earthquakes in western Nepal (Galetzka et al., 2015; Avouac et al., 2015). Moreover, given the estimate of average earthquake return period in western Nepal (Lavé and Avouac, 2001; Stevens and Avouac, 2016; Bollinger et al., 2014), the area of the 1505 A.D. earthquake in the western part of the country is already highly prone for a major (M > 8) megathrust event. The earthquake vulnerability of the country is so serious that Kathmandu, the capital city of Nepal, was ranked first among the 21 investigated mega-cities in the world from the point of view of earthquake risk (Upreti and Yoshida, 2009).

#### 1.1.3.4 Seismic hazard and comparison to other countries

Seismic hazard is the probability of an earthquake, which may cause injury or the loss of life, property damage, social and economic disruption, or environmental degradation.
Seismic hazard associated with potential seismic events in a particular area can be represented by the probabilistic seismic hazard map (PSHM). Deterministic assessment is an alternative method for hazard analysis and is based on a specific earthquake scenario. PSHM is widely applied for earthquake risk mitigation and emergency response. It combines available information on probabilistic evaluations of earthquake occurrence and evaluations on strong motion in the region. In detail, current knowledge on (i) faults and seismic sources in the region, (ii) the behavior of seismic waves' travels through the region, and (iii) near-surface local site effect are taken into account for PSHM. The PSHMs can be prepared by calculating the probability in a given region when it will experience ground motion intensity exceeding a certain limit within a reliable time period.

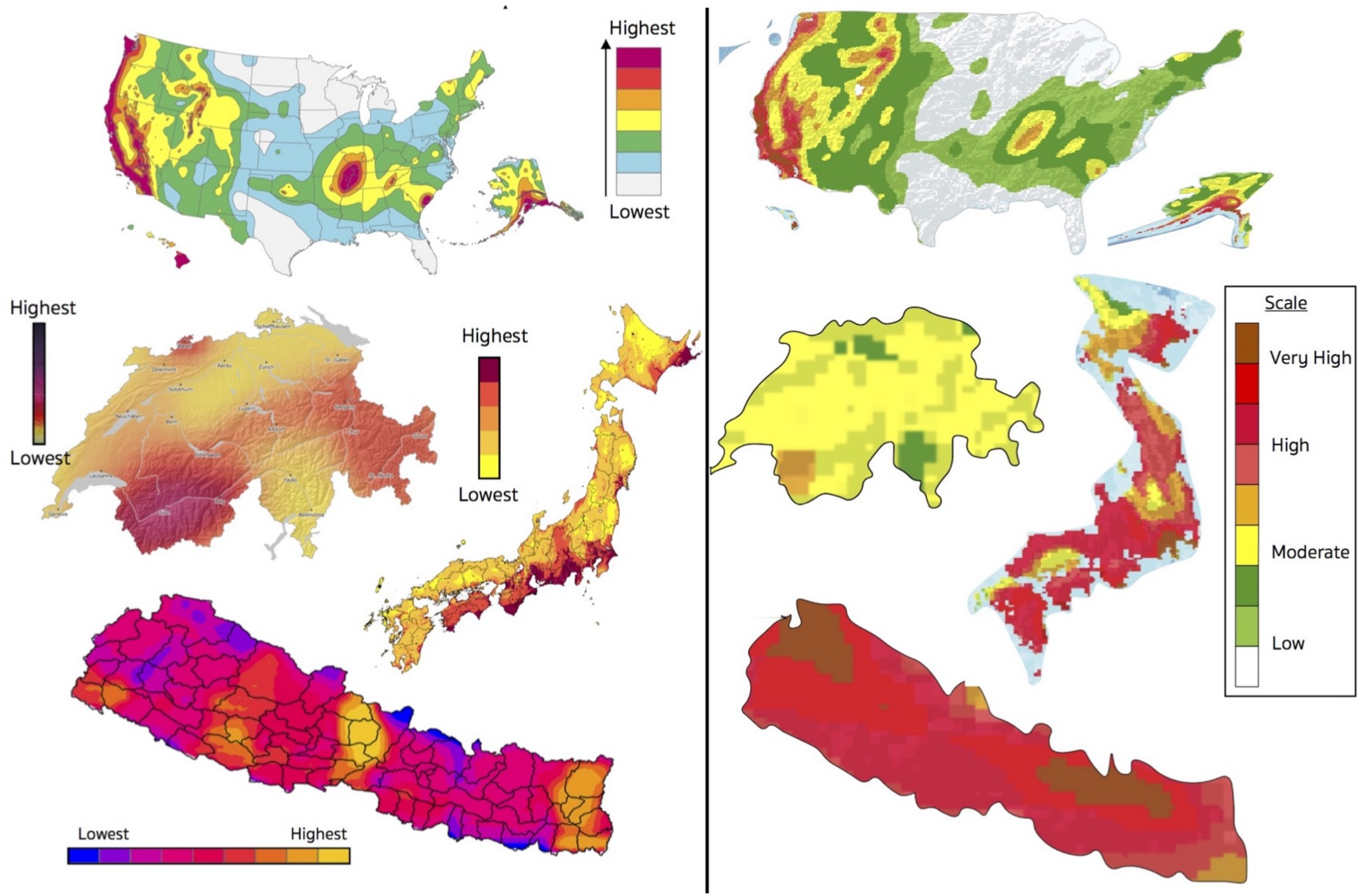


**Figure 1.5:** *Probabilistic Seismic Hazard map comparison. Left: recent seismic hazard maps showing peak ground accelerations having a 2 % (for the USA) and 10 % (for Japan, Switzerland and Nepal) probability of being exceeded in 50 years. Different color scales are used for different countries. Source: USA (USGS), Japan (Geller, 2011), Switzerland (SED) and Nepal (Stevens et al., 2018). Right: Global Earthquake hazard map showing peak ground accelerations ground accelerations having a 10 % probability of being exceeded in 50 years. Same color scale is used for all countries. Source: Giardini et al. (1999).*

The answer why all these parameters mentioned above are important for the PSHM is described as follows. The study of the past earthquakes is the first step to investigate the seismic source. The concernps over the seismic risk in the area are driven not only by the high rate of seismicity but also by the extreme vulnerability of structures and infrastructures. For this reason, construction quality is considered to estimate the relative damage and loss. Moreover, local site effects are also an important factor in establishing the potential damage from major earthquakes. For example, Mexico City in Mexico and Kathmandu city in Nepal are located in thick sedimentary basins, which can amplify the incoming seismic waves resulting in more shaking and therefore more damage. Estimates for the number of casualties, property damage, and economic loss due to earthquakes depend on reliable estimates of seismic hazard and risk. The government including decision makers, engineers, planners, emergency response officials, universities, and local people require seismic hazard estimation for seismically reinforced constructions (building codes), emergency response preparedness plans, and many more types of risk mitigation measures.

**United States of America**

The USGS seismic hazard map represents peak ground acceleration (PGA) with a 2 % probability of exceedance in 50 years. The highest seismic hazard values are along the plate boundary regions of the western contiguous U.S, Alaska, and southeastern Hawaii (Fig. 1.5). The highest hazard values are along the on-shore portion of the active San Andreas Fault (California). In general, regions in the western USA having relatively high seismicity and active faults or subduction zones are the areas for relatively high seismic hazard. Large portions of the central and eastern United States have a relatively lower level of seismic hazard.

**Switzerland**

Damaging earthquakes are rare in Switzerland; however, they pose the greatest damage potential of all-natural hazards. Switzerland is a moderate earthquake-hazard country, and earthquakes are ranked in the third place in terms of risk following electricity shortages and pandemics (OFPP, 2015). The largest earthquake in the history of Switzerland occurred in 1356 in Basel, and is estimated at magnitude 6.6; in the modern period, the most important event occurred in 1946 in Valais canton, with magnitude 5.8 and strong aftershocks (Fäh et al., 2011). According to Swiss Seismological Service (SED), one of the mountainous cantons of the country, Valais is the region at highest hazard, followed by Basel and Grisons (Fig. 1.5). Earthquakes can occur all over the country and there is no area where the seismic hazard may be ignored.

**Japan**

Earthquakes are one of the major natural hazards in Japan. The Mw 9.1 Tohoku earthquake in 2011 is the largest event recorded in the history of Japan causing more than 15’000 casualties. In Figure 1.5 (left), Japan’s seismic hazard map represents the probability of ground motion of seismic intensity of level “6-lower” in the 30-year period starting January

2010. The tectonic setting of Japan falls in an active region, the region of Pacific 'Ring of Fire', where numerous plates form a long zone of subductions. Large earthquakes with a high probability of occurrence in the subduction zone of the Philippine Sea plate results in the highest seismic hazard values in Southern Japan. It reflects the fact that most of the regions in Japan are classified as very high seismic hazard zones.

**Nepal**

In Nepal, the entire country is associated with high seismic hazard values. In comparison, very high seismic hazard zones are observed along the Main Himalayan Thrust, the region where large number of people live in major cities. As presented in the 1999 global seismic hazard map, that eastern region, where the most recent 2015 Gorkha earthquake occurred, and the far-western region, where a major earthquake is already due, are associated with very high hazard values (brown), whereas the other regions are assigned high hazard values (reddish colors). Very little parts of Nepal can be categorized in lower seismic hazard region (Fig. 1.5).

Figure 1.5 also intends to highlight the influence of a map's color code on seismic hazard perception. On the left, individually compiled national maps are presented, with each its own color palette and saturation level. On the right, excerpts from a global map are shown, using the exact same scale, which highlight the relative differences between the USA, Switzerland, Japan and Nepal.

### 1.1.4 Seismic risk and vulnerability

#### 1.1.4.1 Seismic risk

The probability of a hazard event causing harmful consequences is called risk. Seismic risk can be defined as a combination of the probability of a seismic event and the likelihoods of its negative consequences (Beer and Ismail, 2003; UNISDR, UNDP et al., 2009).

The seismic risk, the probability of harmful consequences (expected losses of lives, property and damage) due to an earthquake can be estimated from interactions between seismic hazard (H) and vulnerability (V), where exposure elements are considered as a part of vulnerability. Conventionally, seismic risk (R) is expressed quantitatively by the convolution of these two parameters (e.g., Keilis-Borok et al., 1973):

$$\text{Risk} = \text{Hazard} \otimes \text{Vulnerability}$$

An earthquake is considered as hazard for the computation of seismic risk. The vulnerability to earthquakes depends on several factors including the quality of building structures, ground conditions, and the population distribution. A rapid growth of population, densely constructed civil and industrial buildings, land and water instabilities, and the lack of public awareness regarding the seismic hazard contribute to increase the vulnerability in big cities

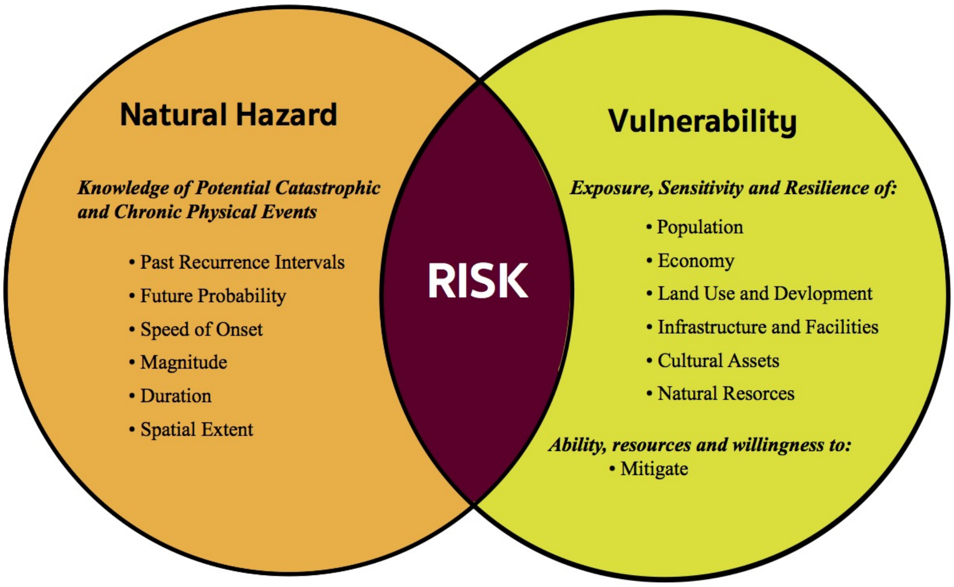


**Figure 1.6:** *Risk of Disaster Diagram. Source: Rainer and Wood (2011).*

(Babayev et al., 2010). People differ in their exposure to risk as a result of their social group, gender, religion, age and other factors.

Why earthquake prediction is not possible is the most frequently asked question from the people in Nepal, and it is a good question as compared to their level of knowledge. The topic of earthquake prediction has been widely debated in the geoscience community and different opinions vary from the statement that earthquake prediction is intrinsically impossible (Geller et al., 1997) to the statement that prediction is possible, but difficult (Knopoff, 1999). However, as of today, earthquake prediction does not exist in any way close to reliable. Therefore, to reduce risk, one should reduce the hazard and/or reduce the vulnerability or exposure of the elements at risk. In most cases, it is almost impossible to reduce the possibility of an earthquake (unless it is human induced) as it is a natural phenomenon, then remaining two factors (which are vulnerability and exposure) determine the corresponding seismic risk (Fig. 1.6).
The same magnitude earthquake can result in different risk levels depending on the values of vulnerability and exposure. The most extreme events in history like the Mw 8.8 Lisbon 1755; Mw 7.9 San Francisco 1906; Mw 8.2 Nepal 1934; Mw 9.5 Chile 1960; Mw 9.2 Sumatra-Andaman 2004; Mw 7.9 Sichuan 2008; and the Mw 9.0 Tohoku 2011 earthquakes are high risk events as they caused casualties and property damage/loss to a great extent. On the other hand, some great earthquakes around the Pacific seismic belt like the Mw 8.3 Okhotsk Sea 2013; Mw 7.9 Papua New Guinea 2016; and the Mw 8.2 Fiji 2018 fortunately, do not lead to similarly large disasters and such damage.

#### 1.1.4.2 Vulnerability

Vulnerability in this context can be defined as the diminished capacity of an individual or group to anticipate, cope with, resist and recover from the impact of an earthquake. To reduce the vulnerability, impact of the hazard needs to be lowered through mitigation efforts and by raising awareness. Earthquake preparedness is crucial to lower vulnerability as a lack of preparedness may result in a slower response to a disaster, leading to greater loss of life. It is also obligatory to improve the buildings' capacities to tolerate and cope with earthquakes. In the following subsections, two main vulnerability components in Nepal are described in detail: constructions and education.

##### 1.1.4.2.1 Construction quality in Nepal

In Nepal, the distribution of the buildings is similar to the distribution of the population, both being higher mainly in Terai region and in main cities. The level of building damage during an earthquake depends on the intensity of ground shaking and seismic performance of the structures. Since classification of the building structure is a basic step to estimate the damage/loss from the related hazard, buildings in Nepal are categorized in brick/stones with mud mortar (BM/SM), wooden (W), brick/stones with cement mortar (BC/SC), reinforced concrete cemented (RCC) and adobe (A). Information on a total

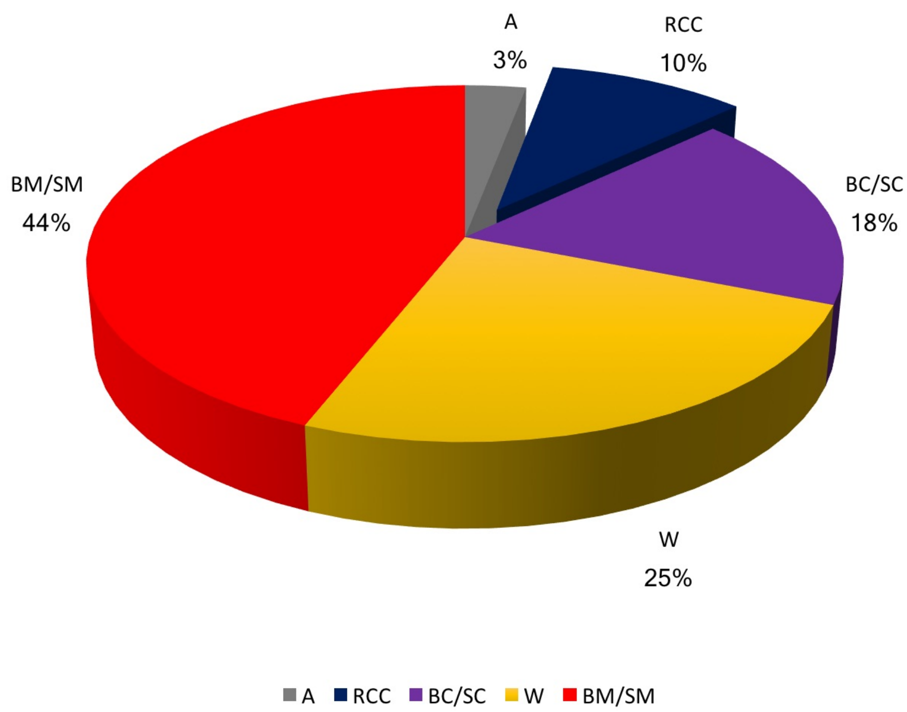


**Figure 1.7:** *Statistics of building types in Nepal (CBS, 2012). Abbreviations: A: Adobe; RCC: Reinforced Concrete Cemented; BC/SC: Brick or Stones with Cement mortar; W: wooden; BM/SM: Brick or Stones with Mud mortar.*

number of 5’423’297 individual households, collected by the National Population and Housing Census in 2011, indicates that the adobe construction, wooden houses and brick/stone masonry buildings are dominating construction types in rural Nepal. Additionally, density of brick/stones with cement mortar and reinforced concrete cement buildings are higher in Terai region and big cities including Kathmandu valley, resulting in 17.57 % and 9.94 % of the building stock, respectively.

More than 40 % buildings are brick/stone masonry, however, RCC constructions are limited to 10 % (Fig. 1.7). About 3 % of buildings fall under the adobe category, which stands for the buildings classified as mixed, others, and not clearly defined in the survey and therefore, similar seismic vulnerability is expected. As 90 % of buildings in Nepal are made by the wood, stone, mud or/and brick in traditional ways, it is important to note here that the majority of RCC buildings are also built by non-engineers, without following proper building codes (CBS, 2012). Similarly, to other developing countries, most buildings in Nepal are built by the owner, and builders who follow the advice of local craftsmen. They are typically not aware of the possible consequences due to forthcoming earthquakes. Having information related to safer building practices and application of simple earthquake-resisting features at nominal extra cost should be a solution to improve the quality while constructing buildings, but neither the house owner nor the craftsmen care about these. Controls and regulations from the government for upholding earthquake resistant constructions are either not applied or applied but not implemented. The professionals’ involvement in the housing sector are not yet self-regulating with respect to good practices (Parajuli et al., 2000).

As a result of repeated shaking through history, it is documented that a large number of buildings were destroyed in Nepal. A total of 18’000 buildings either collapsed or were damaged by the Mw 7.7 earthquake in 1833 with maximum intensity X. The 1934 Bihar–Nepal earthquake (Mw 8.2) with maximum intensity X, had caused damage of 207’248 buildings (Rana, 1935). In 1988, an earthquake of Mw 6.4 with maximum intensity VIII destroyed 66’541 buildings: 22’695 were collapsed and 43’846 damaged (Thapa, 1988). As a result of the 2015 Mw 7.8 earthquake, at least 498’852 private houses and 2’656 government buildings were destroyed. Likewise, another 256’697 private houses and 3’622 government buildings were partially damaged. In addition to this, 19’000 school classrooms were destroyed and 11’000 were damaged (MoHA, 2015). Note that the 2015 earthquake scenario was a relatively favorable one, considering the accumulated seismic moment deficit.

Some works report investigating the effect on buildings in a scenario of recurring past earthquakes in Nepal, and also in different scenarios of possible future earthquakes. The hypothetical recurrence of the Mw 8.2 1934 earthquake suggests that about 22 % of adobe, 9 % of BM/SM, 7 % of BC/SC, and 8 % of RCC buildings would collapse, which means that about 14 % of the buildings would experience extensive damage, whereas the overall collapse of buildings would be limited to 7 % (Chaulagain et al., 2015). The total economic loss would be about 14 billion USD, which is about 48 % of Nepalese gross domestic product

**Figure 1.8:** *Historic Kathmandu tower 'Dharahara' before and after the 2015 Gorkha earthquake. This is an example of brick/stones masonry building. (Courtesy: Narendra Shrestha, EPA).*

(GDP) in 2019; this seems to be an underestimate as the Mw 7.8 earthquake in 2015 caused a 50 % GDP loss. In another scenario, it is expected that 50 % of the buildings would be damaged and 1.3 % of the population would pass away in case of a Mw 8.0 earthquake hits nearby the Kathmandu Valley (Dixit et al., 2000; JICA, 2002). Similarly, in western Nepal, a minimum number of deaths of about 15'000 in sparsely inhabited areas and a maximum of about 150'000 deaths in a densely populated area for a Mw 8.1 earthquake is forecasted. The number of injuries is expected to range from 40'000 to 250'000 (Thieme and Wyss, 2005). The poor socio-economic conditions and uncontrolled building construction practices in Nepal typically cause far greater losses from earthquakes than in developed countries (Fig. 1.8).

Non-engineered constructions are enhancing the vulnerability, and following the seismically reinforced construction practices utilizing proper building code is the only way to reduce the building vulnerability. After the 2015 earthquake, the trend of RCC buildings became more popular. In city areas, some municipalities are setting construction design with updated building codes, but the economic constraints, limited availability of construction materials and technology, lack of proper design, lack in strong enforcement ('must') of building regulations from the government at all levels are still lowering the construction quality and increasing the vulnerability of buildings. People seem to become inspired for making anti-seismic constructions at the time of big earthquakes, but unfortunately, after some time when normal life routine resumes, the whole issue is once again easily forgotten.

#### 1.1.4.2.2 Education: awareness as part of vulnerability

It is only in 1951, following the birth of democracy in Nepal, that people had access to education and societies were allowed to establish schools. There are mainly two types of schools in Nepal, public and private. Private schools are situated in urban areas, whereas public schools are spread all over the country, cities as well as in remote areas.
The school program (Table 1.2) begins with the basic (primary) level, and school starting age for children is five years old, but is not strongly enforced. School education is categorized in basic and secondary level. Following the basic level from grades 1 to 8 and, grades 9 to 12 are classified as secondary level. Higher education is available in universities. As of 2016, a total 35’222 schools are currently operational, where a total of 8’419’511 students study, which is nearly 30 % of the total population (ca. 29 million). Western Nepal, the region of the project presented in this thesis, hosts 22 % of the schools with 20 % of the students.

| Education level | Grade | Student’s age | No. of schools | Students |
|---|---|---|---|---|
| Early childhood | | $< 5$ | 36’568 | 958’127 |
| Basic | 1 – 5 | 5 – 9 | 35’211 | 3’970’016 |
| | 6 – 8 | 10 – 12 | 15’632 | 1’866’716 |
| Secondary | 9 – 10 | 13 – 14 | 9’447 | 970’720 |
| | 11 – 12 | 15 – 16 | 3’781 | 584’072 |
| University campuses | Bachelor & above | $> 16$ | 15(1’407) | 361’077 |
| **Total** | | | | **8’710’728** |

**Table 1.2:** *Education system in Nepal and key numbers, according to Department of Education (MoE, 2017).*

Science is a compulsory subject included in the curriculum of the basic level, within which specific branches of science such as physics, chemistry, botany, biology and others become part of curriculum only after grade 10. Even though the government of Nepal revises the curriculum regularly, seismology is not included till now. This is a desperate situation as there is no information on earthquakes in high school education in a highly earthquake prone country, and therefore people in the local communities have no basic idea about it, and are adopting religious ideas about earthquakes.

The subject of earthquake knowledge and its awareness is too far to be comprehended by local people alone. The scenario is even worse in rural areas where most of the youngsters are outside the village either to study or to earn money. If the concept and knowledge of seismology was introduced as the part of compulsory curriculum already at the basic level of education system in Nepal, students could and would be responsible to lead the community towards an earthquake safer environment; but unfortunately, this is not the case.

Whether people prepare for future earthquakes or not can be significantly influenced by their education and their engagement on related activities (Tanaka, 2005). Following this fact, earthquake awareness is considered as part of vulnerability. Implementation of educational program in schools to make students aware of natural hazards and preparedness is an effective tool to lower their vulnerability. Emergency evacuation drills and trainings for students related to earthquake hazards can be performed to improve personal safety of students and to transfer these ideas to the public. Information on what causes an earthquake, what to do before, during and after the shaking, is momentous for better preparedness. To receive such information at school in the current conditions is barely possible for the simple reason that earthquake education is not included in the curriculum. Training on how to cope with natural hazards is, – though wrongly, – apparently far from the activities that students themselves can do at school.

Even after the 2015 Gorkha earthquake, the common conclusion from different studies is that the accumulated seismic moment beneath western Nepal is sufficient to produce a great earthquake at any time in the near future. In addition, the expected return period for the most recent great earthquake in western Nepal, in 1505, is now over, thus this region is already due for a great earthquake. The real ground scenario is out of imagination. The community awareness level for these scenarios is very low, and people are unprepared, students are unable to cope with future earthquakes' impact, and more than 90 % of the buildings are highly vulnerable. If a M>8 earthquake happens in the near future as according to the scientists, it is for me highly terrifying to imagine the situation and the aftermaths.

### 1.1.5 Motivation

#### 1.1.5.1 Gap between scientific community and society

Earthquakes become a hot topic for discussion in Nepali newspaper and media when a big event happens in Nepal. A governmental institution established for seismic monitoring in Nepal is the National Seismological Center (NSC), under the framework of Department of Mines and Geology, part of the Ministry of Industry, Commerce and Supplies, located in Kathmandu, and in collaboration with France. The NSC is responsible for seismic monitoring and publishes new events on its website, but the local people are looking for earthquake education to understand its process and for better preparedness. There is a gap between what NSC's mandate and the need of local people for better insights on earthquakes.

The National Society of Earthquake Technology (NSET) is a national NGO working in the earthquake domain in collaboration with different international NGOs since a couple of decades in Nepal. The seismic safety improvement project of public schools, disaster risk management initiatives for earthquakes, retrofitting of buildings affected by Gorkha earthquake are some major contribution to the community by NSET. However, NSET's activity is typically focused on Kathmandu or in a particular district in the interseismic period.

The government of Nepal has declared a National Earthquake Safety Day, on the day of the 1934 earthquake. Each year since over 20 years, on the second day of Nepali month Magh (January 15 or 16), National Earthquake Safety Day is commemorated in the country to lay emphasis on disaster preparedness and readiness. The safety day is specially celebrated in Kathmandu valley by organizing seminars, rallies and awareness gatherings. These activities are mainly organizing by governmental authorities in co-operation with (inter)national NGOs where the public is encouraged to participate.

Graduated university students would be good candidates for sharing knowledge in high schools as a role of teacher, but none of the universities include seismology in their official curriculum. Recently, the Physics Department at Tribhuvan University has proposed a course on Solid Earth Physics as an element paper in the Master's degree, but there is no manpower available to teach. Actually, the Nepali education system has been unable to produce seismologists so far. However, the Department of Geology at Tribhuvan University does a lot of research in geological sciences. Geology is one root for the geophysics, but the physics root of seismology to study earthquakes and its processes is still missing even at the University level curriculum.

There were a number of temporary seismological networks installed in Nepal to image the structure of the orogen at depth and to study the seismicity, but they were all short-lived due to the foreign research funding schemes. I have worked on a temporary network data and found first order information about the crustal structure in western Nepal (see Chapter 2). Numerous important findings in the geoscience domain are documented using data from these networks. However, the local population has almost no information about these recent findings. Citizens' awareness is a key element for seismic risk mitigation, which is clearly missing in the field. Some efforts made by various organizations after the 2015 Gorkha earthquake around the capital city, Kathmandu were initiated, but these have not reached to the people in the countryside. The majority of Nepal's population has either a mythological perception or no clear idea about what causes earthquakes and what is the best behavior and practice to protect themselves. In addition, ways to communicate about earthquakes and related topics are not well established in the community. With these strong evidences, I was strongly motivated to establish an educational seismology program, which we named **'Seismology at School in Nepal'**.

#### 1.1.5.2 The 2015 Gorkha earthquake, a decisive turning point for me

Adding a personal coincidence to the introduction, I was in Kathmandu for taking my university physics exams when the 2015 Gorkha earthquake hit Nepal. With its outcomes, I came to witness the injuries of my friends, and the damage and collapse of many infrastructures around me. The earthquake was smaller than expected by the scientists, and the country was not prepared. Actually, at that time even I was not aware about the possibility of such an earthquake happening in my country. At the same time, I came to acknowledge that many people were compelled to lose their lives just because of the lack of understanding of what an earthquake actually is and what precautions are needed to be applied during its occurrence. Because of the lack of knowledge of many Nepalese to avoid or to overcome the devastation of earthquakes, I am highly motivated to bring about a ripple change and reduce the effects from its shock at least by spreading awareness about the cause, effect and its remedial measures. I realized that Earth science could contribute directly to the community, and therefore, I am driven and encouraged to further my studies on it by pursuing them in the field of seismology. Hence, the 2015 Gorkha earthquake came out as a turning point in my career from physics to geophysics. Considering the very limited number of Nepali seismologists, I believe that my specialization would be truly useful for both education and research-seismology.

## 1.2 Project plan and implementation

### 1.2.1 Our project and plan

Our 'Seismology at School in Nepal' initiative aims to tackle two challenges with a combined approach, for which we start our program in an area of high seismic hazard, but relatively limited (although not the lowest) level of information in the country. First, it is crucial to increase the awareness of the local population about the fact that they live in a region where the accumulated energy is sufficient to produce a large earthquake. Second, we need to teach and train citizens in the community for better preparedness and what actions they can undertake to lower their chances of being hurt. In the countryside, no other source of information like television and newspapers are easily accessible, and also in towns it is difficult to gather knowledge from these kinds of sources. Hence, we found that the best way to engage people in learning about earthquakes is through the educational system, as the information students receive at school can be transmitted to their families and communities most efficiently.

In practice, we plan to run earthquake related educational activities such as special lectures in classrooms, training for teachers, and teaching with educational materials adapted to the local system. In parallel, we plan to install inexpensive seismometers in Nepali schools, both to facilitate the teaching efforts, and to carry out some research with the network.

### 1.2.2 Website

In Nepal, the access to internet by the population is growing incredibly and it is currently at about 54 %. Social sites like Facebook, Twitter, and Instagram are commonly known to people. Internet is becoming a suitable platform to share information and knowledge with the public. To keep the school's and student's motivation in our program and to share our activities and knowledge continuously with an even broader community, we have developed the program's own website: www.seismoschoolnp.org.

Prepared documents for education, information of recorded earthquakes, guidelines for exercises, important questions and answers, questionnaire for survey of local people are available on the website. All the material of the initial teacher-training workshop is also available. In case of local earthquake inside our network, we also post the waveforms and corresponding station-wise shake maps on the weblink. In advance, if someone is interested to estimate magnitude and distance of local earthquakes from their own school's waveform recording, the related guideline document is also published at our website. This page has been gaining good number of visitors every month.

### 1.2.3 Low-cost seismic network

The experience we have had during our high school courses is that practical knowledge lasts longer compared to theory. The installation of a low-cost seismometer in a school will improve the earthquake understanding capacity of students and will help to keep the knowledge for long in their minds. The seismic sensors should achieve two different goals of the program, mainly to be able to detect relatively low magnitude earthquakes, and to be able to be used as a teaching instrument to share knowledge with students in an efficient way in the classroom.

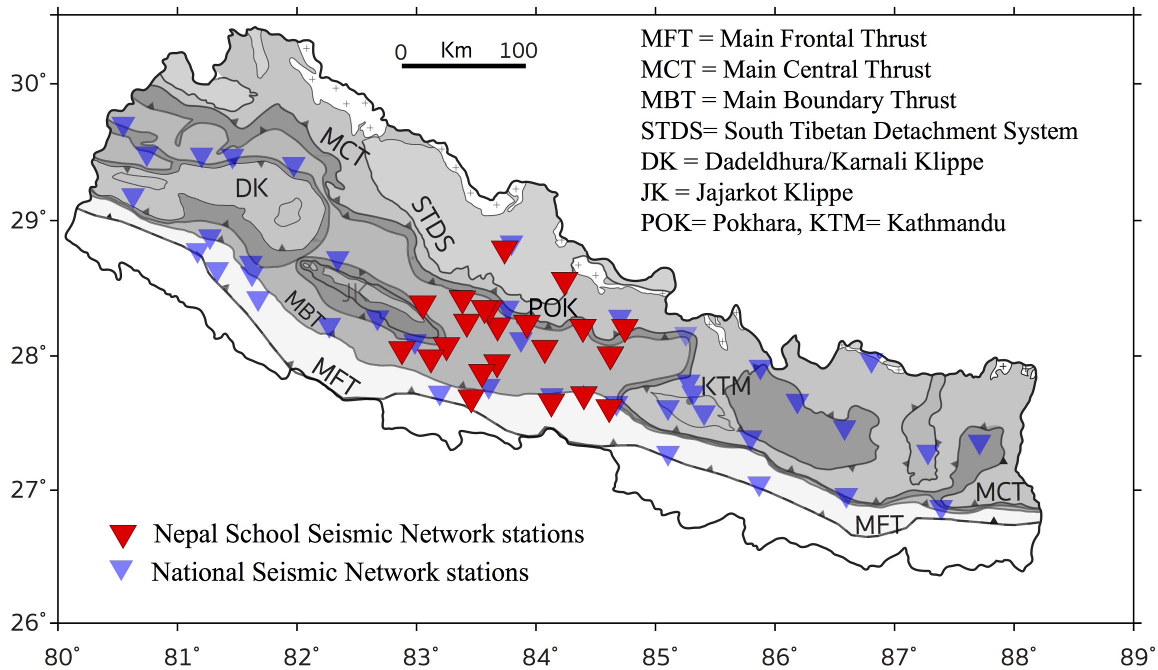


**Figure 1.9:** *Seismic networks in Nepal. Blue inverted triangles are NSC stations and red inverted triangles are newly installed low-cost stations forming the NSSN. About 50 % of NSC stations have been installed after the Gorkha earthquake, mostly after 2018 in collaboration with different institutions around the world (Source: NSC). KTM is the federal capital Kathmandu, and POK is a provincial capital Pokhara. Geological map in the background are from Robinson and Martin (2014).*

To this end, we installed the first 22 low-cost seismic stations in schools to create the Nepal School Seismic Network (NSSN) (Fig. 1.9). This network is already used both for the teaching activities and for sharing the locally recorded data openly. Data can be downloaded by anyone via the Raspberry Shake server (https://fdsnws.raspberryshakedata.com/). Further details are described in Chapter 4. The network is one of the main tools to connect local communities with citizen science in Nepal.

### 1.2.4 Scientific communication

A good scientific communication strategy could play a role in reducing the seismic risk, to save lives during the big earthquake, and to help survivors in the days, weeks, and months after the mainshock to recover from the earthquake. In Nepal, we confirm that people need earthquake information with advice on protective actions and self-care strategies. Since this project is running in the school, we have trained teachers, students, and local people. Some evidence during the most recent earthquake in 2015 shows that earthquake awareness documents already existed but were incomplete and at some point, they lead to misunderstanding, e.g., the people's mindset is going under the table in case of an earthquake, which is completely wrong for those who are outside the buildings. Besides, 'drop cover and hold' will not work for the majority of buildings as they are not earthquake resistant. With this background, we paid more attention to deliver correct and practical information. The physics of earthquakes, seismic waves and their natures, plate tectonics, earthquake magnitude and intensity, the frequency response for different kinds of buildings and ultimately what to do before during and after the earthquake, etc. are topics we have taught and communicated with teachers in the workshop and also during the school visits. For students, we focused mainly on teaching earthquake knowledge and preparedness topics and encourage them to transfer the new knowledge to their family and community. We also used animations and demonstrations from the Earth Learning Ideas (ELI) webpage which is a platform to collect Earth-related teaching ideas where teaching strategy, teaching ideas, and teaching videos are available for earthquakes and other natural disasters. For the details of the earthquake information and preparation, we distributed a 'be prepared' flyer to students and teachers. Apart from these documents, we also discussed all raised questions not only related to the earthquakes but also general science by teachers and students. We hope such discussions are helpful to develop some ideas for a better understanding of Earth's behavior and to learn about earthquakes.

## 1.3 Citizen and educational seismology initiatives

### 1.3.1 Similar projects around the world

Geosciences are widely applicable in various fields including mapping of Earth structure at various spatial and time scales, water, ore and hydrocarbon exploration, natural hazard analysis and risk mitigation, and many more. The study of earthquakes and related properties and processes belong to the field of seismology, within which many scientists do classical research while others engage in initiatives for education and outreach purposes, typically in the frame of education and/or citizen seismology programs. The seismometer deployment history for education and citizen seismology is presented in Table 1.3, and the number of seismometers installed for education purposes are presented in Figure 1.10.

The Princeton Earth Physics Project (PEPP) started in the United States in 1994, and was a groundbreaking experience in the domain of educational seismology. Europe has a long history of education and citizen seismology programs including the Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation (NERA) and the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) projects funded by European Union in European countries.

The concept of educational seismology in Europe came from France, and the French project started in 1996 (Virieux, 2000) with the aim of giving students a taste of science through original projects, that allows them to do in-depth work and follow-up activities investigating earthquakes with their teachers and seismologists. The project enables the promotion of seismology through hands-on experiences, increasing awareness of seismic hazards, developing awareness and responsibility among young people, and producing high-quality seismic data with the 'Sismos à l'Ecole' (SaE) program since 2006 (Courboulex et al., 2012). In France, seismology is in the curriculum and SaE is an example of a successful project in educational seismology where a total of 60 high-quality seismic instruments are installed in schools and a further 12 stations are situated in overseas territories outside mainland France (Berenguer et al., 2010, 2013).

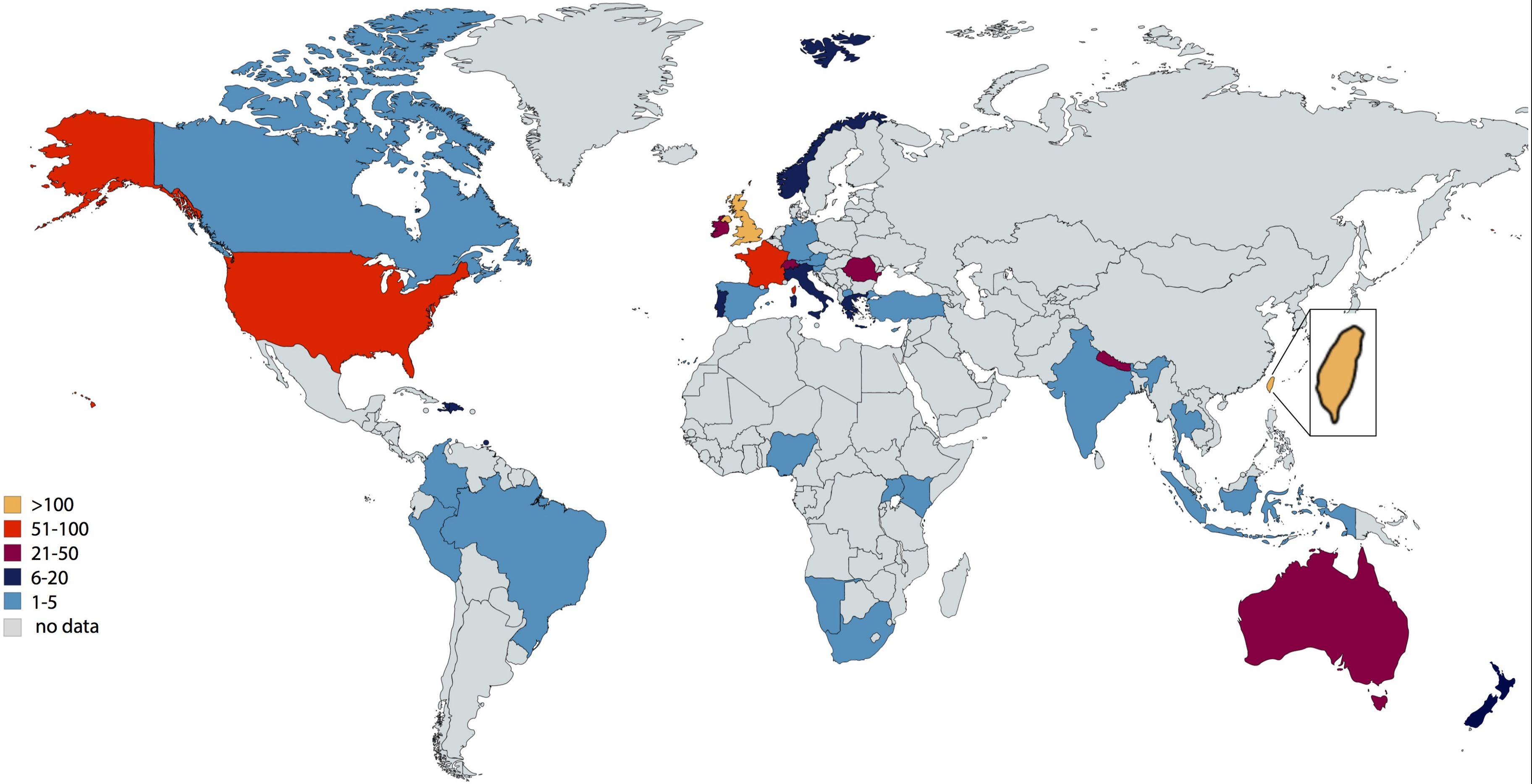


**Figure 1.10:** *Number of seismometers installed for education purposes around the world, by country. Source: own compilation based on respective project information (as of June 2019).*

In Switzerland, the Seismo@School program started in 2008 by the combined effort of HES-SO, Valais-Wallis, Sion, and the Swiss Seismological Service (SED) at ETH Zurich. This was a general resource center for educational activities in seismology and provides seismic data and general information to the public. Also, Seismo@School distributes a rich collection of earthquake data, movies, and various educational materials freely. In addition, the Centre for Earthquake Education and Prevention (CPPS), in Sion, Valais offers training to young people and the wider population for a better understanding of the occurrence of earthquakes, learning how to protect and make better preparations in case of an event. An earthquake simulator of 5 by 6 meters with 2D motion is also installed, which can simulate shaking corresponding to an earthquake up to M 8. This is an excellent laboratory for students to learn the behavior of seismic waves. Seismo@School has completed its first phase and is planning further steps (Zollo et al., 2014).
Educational seismology programs are applicable not only to increase earthquake awareness and preparation, but also to motivate students to pursue a career in geosciences. In the decade of 1990s, the number of students studying physics in the UK has dropped by 50 % (Zollo et al., 2014). The UK school seismology project, running since 2007, aims to make science more interesting for students aged 11 - 16, to increase the number of 16+ students in physical science, and to influence the government for the inclusion of seismology and Earth science topics into the science syllabus (Denton, 2008a,b).

In the United States, a number of science education programs have been operating to define a collaboration between the scientific community and high schools, aiming to inspire careers in geophysics by the better understating of seismology and Earth sciences. The common goals of these programs are to bring seismological data into classrooms across the country and around the world, to improve scientific literacy, to activate student's interest in scientific research, and to provide tools and software for scientific investigations (Hamburger and Taber, 2003). In order to achieve these missions, the Incorporated Research Institutions for Seismology (IRIS) runs Education and Outreach programs across the country. In parallel, some universities are running similar projects on a regional scale, for example the Texas Educational Seismic Project and the Boston College Educational Seismology Project.

| **Year** | **Implemented projects** |
|---|---|
| 1994 | Birth of PEEP project in USA |
| 1996 | Birth of EduSeis project in Europe |
| | First station installed in France and Italy |
| 1997 | IRIS Education and Outreach program in USA |
| 1998 | Five stations installed in Portugal |
| 1999 | Ten stations installed in France |
| 2000 | Several stations installed in Italy |
| | School network in Norway |
| 2004 | Five stations installed in Greece |
| 2006 | Sismos à l'école program extends in France |
| 2007 | UK school seismology project |
| | Seismo at school in Switzerland |
| | European Educational Observatory for Environment project |
| 2009 | School seismology program in Ireland |
| 2010 | NERA project in Europe |
| 2012 | AuSIS network installed in Australia |
| | Romanian educational seismic network |
| 2013 | Citizen science in Taiwan |
| 2015 | Ru seismic network in New Zealand |
| **2017** | SERA project in Europe |
| | Raspberry Shake sensor developed and tested |
| | **Our 'Seismology at School in Nepal' project is planned** |
| **2018** | **Our 'Seismology at School in Nepal' project starts** |
| | Oklahoma educational program in USA |
| | Seismometers in schools pilot project in Indonesia |
| 2019 | City Educational Seismic Network in Spain |

**Table 1.3:** *Brief history of educational and citizen seismology and related projects in various countries. Source: own compilation based on respective project information and personal communications.*

The Australian Seismometers in Schools (AuSIS) program has been running since 2011 in Australia. It is an outreach program where 50 research-quality broadband seismometers are installed in schools around the nation. AuSIS is working to raise community awareness of regional earthquakes, to increase understanding of seismology and – more generally – geosciences, to promote science as a possible future career, and to provide a tool to teachers to assist in teaching physics and Earth science to high school students (Balfour et al., 2014). Moreover, it is also documented that educational seismology programs have been initiated in Norway (Husebye et al., 2003), Romania (Tataru et al., 2016) and Italy (Zollo et al., 2014) to cultivate various interests in science among students and to introduce seismology in classrooms.

### 1.3.2 Lessons learned from similar initiatives

In general, the purpose of the education and citizen seismology approaches around the world is to promote earthquake education to students and the public. However, the focus can change depending on the earthquake risk extent and the awareness level already existing in each society, making earthquake education topical. In particular, in earthquake prone, developing countries like Nepal and Indonesia, it is important to increase awareness and to prepare the community for a future shaking event. However, in developed countries with low earthquake frequency such as United Kingdom and Australia, it can also be useful to keep the students' interest in science by an educational seismology approach.

The SaE project has been supported by French Ministry of Education since 2006 and each school has a direct link with a volunteer seismologist from a nearby university or research laboratory to address technical and scientific concerns. This program acts as a seismic resource center and a platform for educational and scientific activities. In addition, signal analysis software such as Seisgram2K and EDUCARTE have been developed. This project strengthens the interaction between teachers and researchers (Berenguer et al., 2010, 2013). The Seismo@School project was initiated to contribute to science education and the understanding of the Earth system. Stations deployed for the program are routinely used by the Swiss Seismological Service to monitor local seismicity. In parallel, schools also used other sensors like SEP and Quake Catcher Network for educational activities. As the program has stopped currently, maybe it would be better to restart with bottom-up approach with the support of local authorities.

In the UK, based on the teachers' preference, a simple, mechanical sensor with a visible design was preferred over a research quality but 'black-box' seismometer to be installed in schools. Nearly 200 seismometers were installed, and the instrument system was designed to be compatible with already existing software for data analysis. The British Geological Survey ran the UK school seismology project until late 2019, in cooperation with multiple universities across the United Kingdom.

As Australia is not a particularly seismically active country, and therefore more sensitive instruments are needed to record global earthquakes, the AuSIS project installed professional instruments in schools. With 50 seismometer installed across the country, it has been running well since 2011. However, different regulations for education departments in different states, transferring teachers between schools, updated technologies, continuous seismometer operation, IT issues, and students' and the community's engagement in some major problems are typical challenges encountered by the program (Michelle Salmon, AuSIS coordinator, pers. comm.).

In the United States, there are many individual approaches but the main is the IRIS education program with a focus on student engagement to encourage learning and to show them the possibilities of geoscience careers. This includes bringing data into the classroom using jAmaSeis software and the use of educational seismometers. From these projects it is clear that an important element is to provide easy access to data and information for inviting broad audience in citizen science. Furthermore, IRIS provides internship opportunities to undergraduate students for geophysical fieldwork. Data from the NASA InSight mission to study marsquakes is also used to attract students towards geosciences.

The school seismology initiatives are widely appreciated and have been successful in other European countries, too. In Italy an early earthquake warning system for schools has been tested successfully (Picozzi et al., 2015). The Romanian educational seismic network is raising awareness of earthquakes, and also plays a role to include earthquake related courses in high school curriculum.

# Chapter 2

# Imaging the Moho and the Main Himalayan Thrust in Western Nepal With Receiver Functions

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## 2.1 Abstract

The crustal structure of Western Nepal is studied for the first time by performing receiver-function analysis on teleseismic waveforms recorded at 16 seismic stations. The Moho geometry is imaged as it deepens from ∼40 km depth beneath the foothills and the Lesser Himalaya to ∼58 km depth beneath the Higher Himalayan range. A mid-crustal low-velocity zone is detected at ∼15 km depth along ∼55 km horizontal distance and is interpreted as the signature of fluids expelled from rocks descending in the footwall of the Main Himalayan Thrust. Our new image allows structural comparison of the Moho and of the Main Himalayan Thrust geometry along- strike of the Himalayas, and documents long-wavelength lateral variations. The general crustal architecture observed on our images resembles that of Central Nepal, therefore Western Nepal is also expected to be able to host large (Mw>8) megathrust earthquakes, as the 1505 A.D. event.

## 2.2 Introduction

The Himalayas are the result of the Indian and Eurasian plates' convergence (e.g., Aitchison et al., 2007), which takes place at a rate of ∼4 cm/yr. About half of this is accommodated by shortening across the Himalayas (e.g., Zheng et al., 2017) on the Main Himalayan Thrust fault (MHT), the megathrust present under and along the 2'500 km long Himalayan range. The upper segment of the fault is locked between the surface and its down-dip end, located at a depth of ∼20 km under the High Himalayan range (e.g., Bettinelli et al., 2006a). This upper, locked segment of the MHT ruptures partially or entirely during large or great earthquakes, and thereby propagates the strain accumulated at depth during the interseismic period towards the surface (e.g., Avouac et al., 2015).

The largest instrumentally recorded earthquake in Nepal, the 1934 Mw8.2 Bihar-Nepal earthquake, has ruptured a >150 km segment of the MHT from Eastern to Central Nepal (Sapkota et al., 2013). It was followed by the Gorkha earthquake (Mw7.8) and a second event (Mw7.3) in 2015 (e.g., Adhikari et al., 2015) which ruptured a consecutive deep segment of the MHT further west in Central Nepal (Grandin et al., 2015; Avouac et al., 2015; Lindsey et al., 2015; Elliott et al., 2016; Duputel et al., 2016). An earthquake in 1833 with macroseismic effects similar to that of the 2015 event was reported in that same region (Bilham, 1995; Martin et al., 2015), it is therefore possible that the 2015 and 1833 earthquakes have ruptured a similar segment of the MHT. However, further West, no large earthquake is documented in the last 500 years (e.g., Hetényi et al., 2016a) since the occurrence of the major 1505 A.D. earthquake (Ambraseys and Jackson, 2003), leading to a well-identified seismic gap (e.g., Mugnier et al., 2013; Kumar et al., 2006; Rajendran et al., 2015; Khattri, 1987; Bollinger et al., 2016). The Global Positioning System (GPS) velocity field measured through this segment of the orogen demonstrates that the upper portion of the MHT is locked (e.g., Stevens and Avouac, 2016), and may have accumulated as much as ∼10 m of slip deficit. Given the estimate of average earthquake return period along the Himalayas (Avouac et al., 2001; Stevens and Avouac, 2016; Bollinger et al., 2014), the area of the 1505 A.D. earthquake is highly prone for a major (Mw>8) megathrust event.

Since the structure of the crust and the geometry of the MHT are key parameters to better understand seismogenesis and to evaluate seismic hazard, several temporary seismic experiments were deployed to image the crustal structure in Nepal. The HIMNT experiment imaged the structures across a 300-km-long and -wide network (Schulte-Pelkum et al., 2005) in East Nepal and southern Tibet. The Hi-CLIMB experiment has carried out high-resolution imaging of structures along an 800-km-long profile across Central Nepal (Hetényi, 2007; Nábělek et al., 2009) and central Tibet. This dataset allowed (Duputel et al., 2016) to associate the rupture of the 2015 Gorkha earthquake along the flat portion of the MHT with a low-velocity zone constrained by both CMT inversion and P- and S- seismic receiver-function (RF) approach. However, in Western Nepal, there is currently no geophysical image of crustal structures available. The MHT geometry remains therefore elusive, leaving the question of

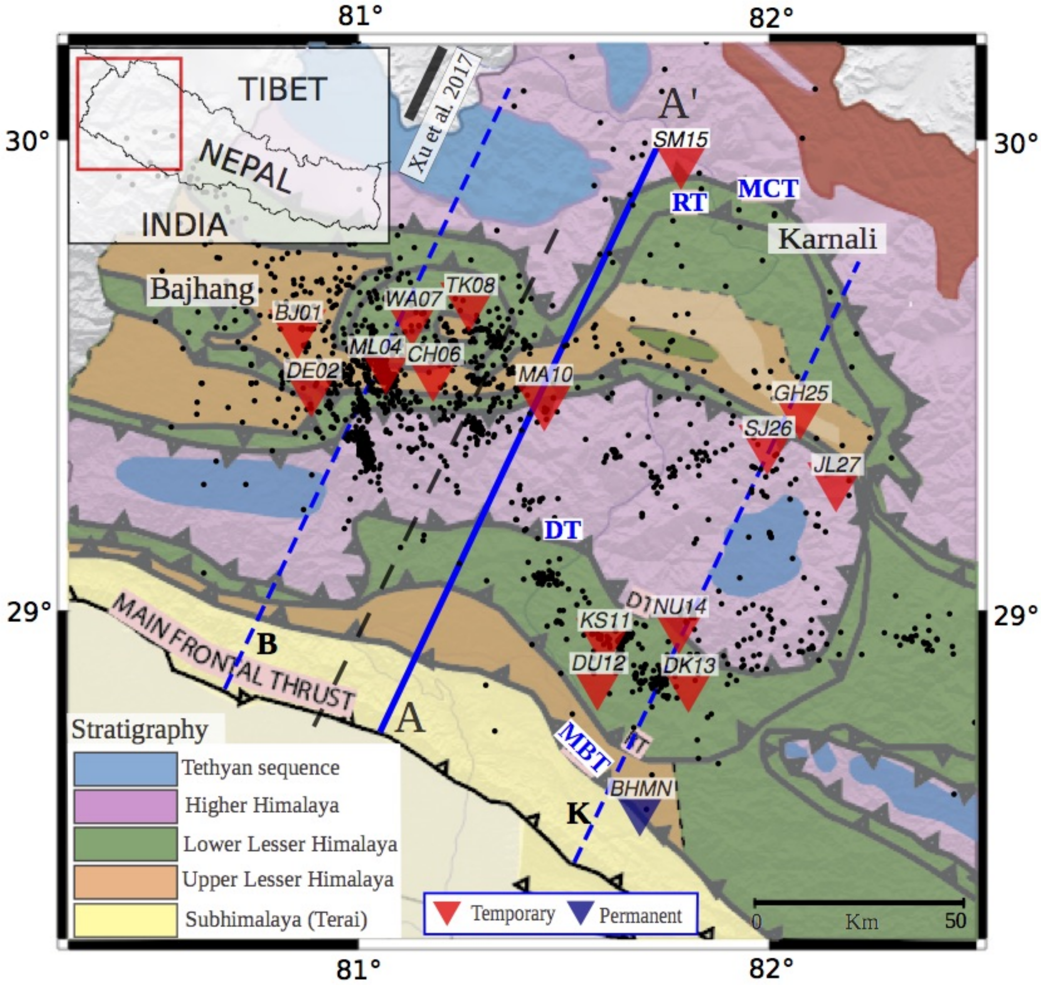


**Figure 2.1:** *Study area in Western Nepal with the simplified geological map from Robinson et al. (2006). South of the Main Frontal Thrust are foreland basin sediments. Seismic stations operated under Hi-KNet are shown as red triangles, and detected seismicity in black dots (Hoste-Colomer et al., 2018). Blue triangle represents a permanent broadband station. Faults: Main Frontal Thrust (MFT), Main Boundary Thrust (MBT), Ramgarh Thrust (RT), Dadeldhura Thrust (DT), Main Central Thrust (MCT). Cross-section AA' is shown on Figures 2.2 and 2.3. The thick black line locates the southern end of Xu et al. (2017) profile (Fig. 2.3). Black dashed line locates the Chainpur geological cross-section (Robinson and McQuarrie, 2012). Blue dashed lines B and K locate the Bajhang and Karnali profiles (Figs S5, S6). Inset locates the map within Nepal.*

the applicability of the Central Nepal seismogenic model in the area of the great 1505 A.D. earthquake open.

Indeed, the surface geology of the fold-and-thrust belt in Western Nepal is significantly different from Central Nepal. It exposes a more complex stack of alternating Lesser Himalayan slivers and crystalline klippe relicts (Fig. 2.1, DeCelles et al., 2001; Arita et al., 1984; Robinson et al., 2006; Robinson and McQuarrie, 2012). The geometry of the fold-and-thrust belt allowed reconstituting balanced cross-sections of the area (Robinson et al., 2006; Robinson and McQuarrie, 2012) that were never confronted with geophysical constraints apart from the regional seismological catalogue (Pandey et al., 1999). This catalogue depicts lateral variations of the seismicity but their hypocentral depths were not well constrained.

A temporary seismic network was recently deployed in Western Nepal to scrutinize regional seismic activity (Hoste-Colomer et al., 2018, Fig. 2.1). In this article, we analyze the data recorded by the same network to image the crustal structure of Western Nepal for the first time. We chose to work with the receiver-function method (e.g., Langston, 1977) which is best suited to map lithospheric discontinuities with sharp velocity changes. This way we primarily aim at the crust-mantle boundary (Moho) and at potential low-velocity zones in the crust, as observed in Central Nepal. We compare our results to other cross-sections across the Himalaya and especially to Central Nepal for structural and seismogenetic aspects.

## 2.3 Data and methods

### 2.3.1 Data

This study is based on data recorded at 15 stations of the first temporary seismic experiment in Western Nepal, the Himalaya-Karnali-Network (Hi-KNet) and permanent station. The Hi-KNet temporary seismic experiment operated 15 stations in Western Nepal between November 2014 and October 2016 (Hoste-Colomer et al., 2018). Hi-KNet was operated by the Département Analyse Surveillance Environnement, France in collaboration with National Seismological Centre, Department of Mines and Geology, Nepal. The permanent station at Bhimchula (BHMN) is run under the Regional Seismological Network of Nepal. All stations were stand-alone and recorded data in continuous mode at a rate of 100 samples per second. For precise time acquisition, the Nanometrics Taurus digitizers were synchronized by GPS. All stations used three-component, broadband or intermediate-period sensors (see Table S1[1]). The network geometry was defined to best analyze local seismicity by covering the different earthquake belts in Western Nepal, thus forming three clusters of stations (Fig. 2.1) with an average station spacing of ∼10 km in each.
For the computation of RFs, we selected Mw $\geq$ 5.5 teleseismic earthquakes at epicentral distances 30°-100° from the USGS earthquake catalogue (Fig. S1[1]). The Hi-KNet recorded 372 such earthquakes during its operation, and station BHMN recorded 160 such events between March 2014 and September 2015.

[1] See suppprting information file at https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018GL080911

### 2.3.2 Receiver function computation

The original ZNE-component data are band-pass filtered between 0.2 - 0.5 Hz for single station analysis and 0.2 - 1 Hz for RF migration (Section 2.3.3). Semi-automatic quality-control criteria were adopted following (Hetényi et al., 2015, 2018) and (Singer et al., 2017). The semi-automatic quality-control criteria are applied to the original ZNE-component waveforms as follows: (a) the root-mean-square (rms) amplitude of the signal computed between 30 s before and 120 s after the P-wave arrival has to be within 1 order of magnitude of the median of all rms values for the same event at other stations, (b) the maximum amplitude of the main P-wave peak has to be at least 1.5 times higher than the maximum amplitude of the preceding 20 s background signal on the Z-component for each trace, and also (c) at least 3 times higher than the rms of this background signal. Seismograms were rotated into the ray-based LQT (P-SV-SH) coordinate system using the theoretical ray-parameter and assumed near-surface velocity (see model description below). This way the direct P-phase is removed during deconvolution, therefore no or little signal should appear at zero lag-time. The Q- and T-components were then deconvolved from the L-component using the time-domain iterative approach of (Ligorria and Ammon, 1999) using 150 iterations, and the spikes convolved with a Gaussian-pulse of a width corresponding to the signal's highest frequency to obtain the final radial and transverse RFs. A visual quality control on RFs discarded few poor-quality and anomalous RFs (e.g., ringing waveforms, no clear Ps phase). Our final dataset consists of 960 high-quality RFs, shown in Figure S2[1] (radial and transverse components) and Figure S3[1] in cross-section view of station-stacked radial RFs along the AA'-profile.

### 2.3.3 Receiver function analysis

In frame of our RF analysis we employ two methods, detailed below. First, a single-station approach to validate that the first order structure of the crust resembles that of the local velocity model chosen for migration in terms of average crustal Vp/Vs. Then, to construct our final images using a more sophisticated approach, we perform pre-stack time-to-depth migration and interpret the results based on those.

To verify the first-order estimate of the crustal structure and average crustal Vp/Vs for each station, we follow the H-K approach (Zhu and Kanamori, 2000) where the time separation between the direct P-phase, the converted Ps-phase and the multiply reverberated phases are exploited (Fig. S4[1]). We consider the extent of the H-K-space–peak (at a nominal 86 % of the maximum amplitude) to estimate the related uncertainties of both values (Table S2[1], Fig. S4[1]). The main goal of this single-station analysis is to see how the derived Vp/Vs-ratios compare with the previously proposed 1-D velocity model, and whether this model can be reasonably used for RF migration. Our results demonstrate that the average crustal Vp/Vs for all except one station (BHMN) justifies the use of a 1-D velocity model in the migration approach.

To produce crustal-scale cross-sections and to draw final interpretations we perform time-to-depth migration and spatially reconstruct the geometries of the subsurface discontinuities causing the wave conversions. We use the widely adopted Common Conversion Point (CCP) migration technique (e.g., Zhu, 2000). The 2-D profile mesh has 1 km horizontal and 0.5 km vertical spacing; ultimately, a 3 km-wide horizontal Gaussian filter is applied to smooth the image. The Ps phase amplitudes of each RF are back-projected to their spatial conversion points along the ray path.We chose the Nepali national velocity model (Pandey et al., 1995) for the ray tracing and time-to-depth conversion, as this is the only available well-constrained model in the broader region (Table S3[1]). At the only station where the average crustal Vp/Vs-estimate (BHMN: 1.60) differs from that of the Nepali velocity model (1.75 - 1.76), we modify the Vs model used in the migration: we create a 1-D model by dividing the Nepali model's Vp by the station's average crustal Vp/Vs obtained from H-K stacking. Other stations do not require correction as they detect Vp/Vs values (1.69 - 1.81) that are similar to that of the Nepali velocity model (1.75 - 1.76). This is corroborated by the Vp/Vs-range of 1.75 $\pm$ 0.06 obtained from Wadati-diagrams generated with 67 events beneath northern Hi-KNet during the experiment (Benoit, 2016). We assess the uncertainty of our Moho depth determinations and conclude that our results are consistent and robust. A Vp/Vs deviation of 0.06 would imply a Moho depth variation of $\sim$4 km for the same delay times. We also compare the H-K stacking- and the CCP migration-derived Moho depth values and cross-check the respective RF phase delay times (Figs. 2.2, S4[1], Table S2[1]), and thus demonstrate that our results are consistent and robust. A mismatch in Moho depth of $\sim$5 km is observed at only three stations, which likely arises from features which our simple 1-D velocity model does not encompass.

Migration results are presented along the AA'-profile (Fig. 2.2) and separately for the Bajhang and Karnali profiles (Figs. S5[1], S6[1]). To extend our main RF profile and the interpretation, we append the migrated RF image of Xu et al. (2017) in southern Tibet (Fig. 2.3), continuing in the same direction and offset by 75 km to the west, properly juxtaposed to our image.

## 2.4 Results

The migrated receiver-function images reveal for the first time the crustal structure of Western Nepal (Fig. 2.2). The consistent, positive (velocity increase with depth) interface is interpreted as the Moho. Despite the lateral spread of stations, the Moho signature is sharp and clear. The observed Moho depth beneath BHMN station is $\sim$40 km, and it slowly increases towards the north, reaching $\sim$58 km beneath the Higher Himalaya. The imaged shape of the Moho is smooth along the AA'-profile except at $\sim$110 km distance where different Moho depths are projected near each other from the Bajhang and Karnali profiles (Figs. S5[1], S6[1]). The maximum Moho depth difference there is $\sim$6 km, and hints at

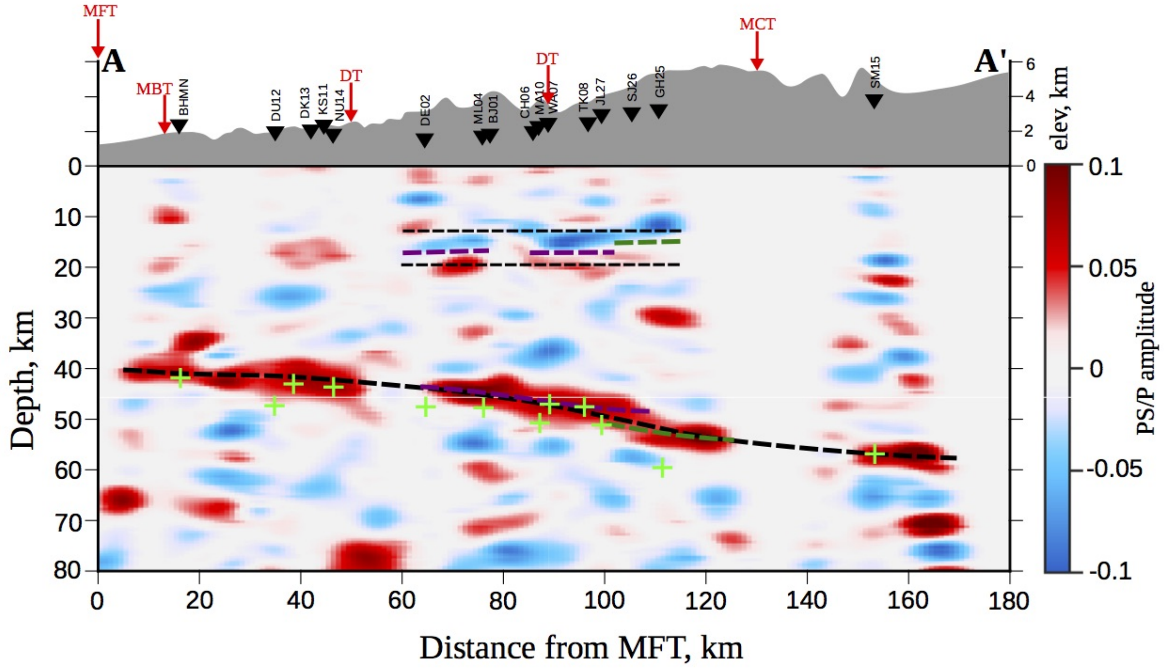


**Figure 2.2:** *P-to-S receiver-function migration imaging the crust. The prominent signal from the Moho and the intra-crustal low velocity zone are highlighted with black dashed line drawing. Green crosses show Moho depths computed from H-K stacking. Dashed purple and green lines are reported from Bajhang and Karnali profiles, respectively (Figs. S5[1], S6[1]), where local lateral variation of Moho depth and/or velocities is hypothesized. Fault name abbreviations as in Figure 2.1. See text for detailed discussion.*

local lateral variations over the ∼100 km distance between the two profiles. This difference could arise from locally varying velocities along the arc, not accounted for by the employed 1-D velocity model.

Besides the Moho the strongest and most continuous signal observed in the crust is a negative-over-positive (blue-over-red) amplitude feature in the central part of the profile. It is present both along the Bajhang and Karnali profiles (Figs. S5[1], S6[1]). The apparent interruption at 80 km distance can be due to shallow, local variations in structure or velocity with respect to the model used during migration. This seismic signature corresponds to a velocity decrease at ∼12 - 14 km depth followed by a velocity increase at ∼18 km depth, indicating the presence of a sub-horizontal, ∼55 km long low-velocity zone (LVZ). It expands between ∼60 and ∼115 km distance north of the Main Frontal Thrust, beneath a region of imbricated thrust sheets (Robinson and McQuarrie, 2012; Hoste-Colomer et al., 2018) of Lesser Himalayan rocks called the main Lesser Himalayan duplex (Figs. 2.1, 2.2). Due to the absence of major velocity discontinuities at shallower depth, it is unlikely that this signal corresponds to multiple reverberations. There can also be some local effects of dip and/or anisotropy, as some stations feature high amplitudes on the transverse RFs. However, we

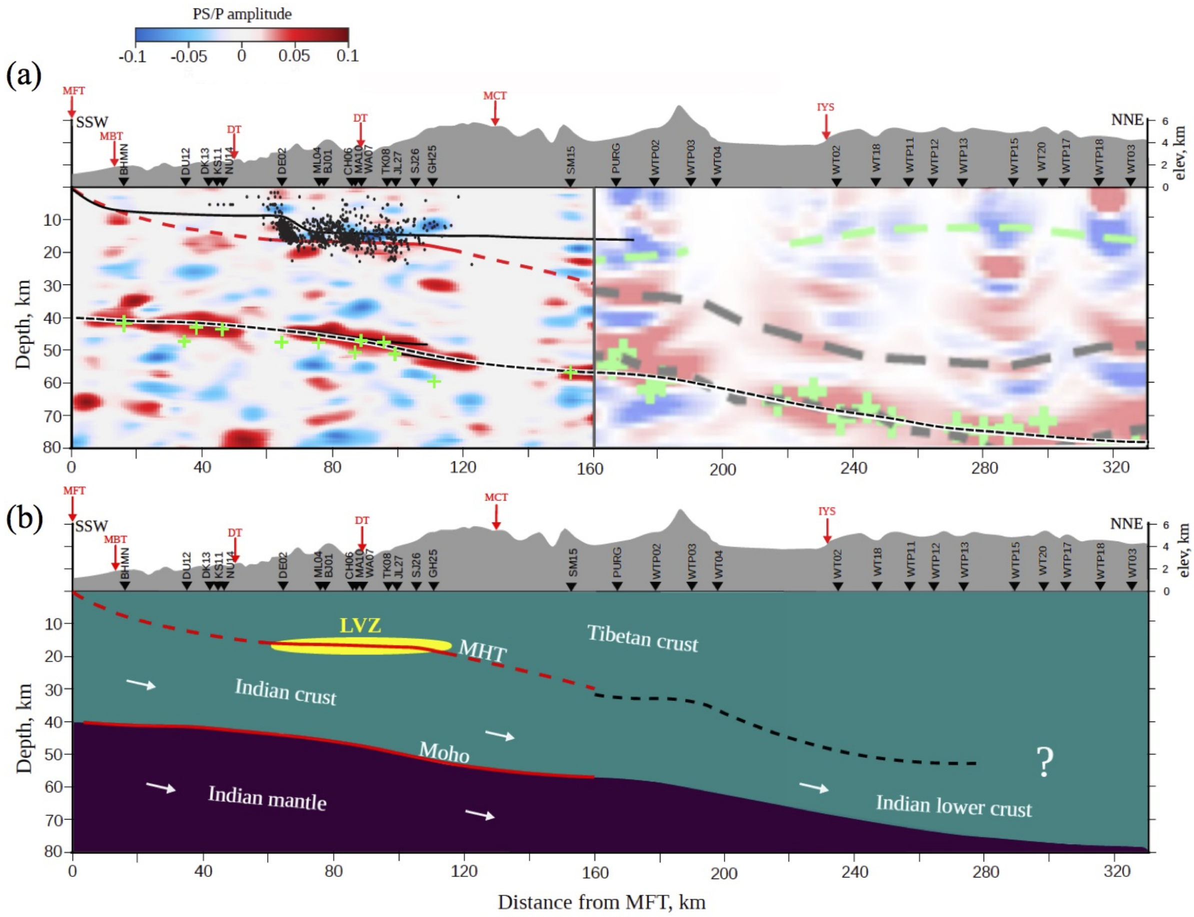


**Figure 2.3:** *Extended profile and interpretation. (a) Composite RF image from Figure 2.2 (left) and from Xu et al. (2017) (right, reduced color intensity). Green crosses: Moho depths derived by H-K stacking in this study. Black dashed line: smoothed, interpreted Moho from CCP migration. Red line: position of the MHT at the central depth of the LVZ, dashed parts are extrapolations. Thick black line: MHT geometry interpreted from geological reconstructions (Robinson and McQuarrie, 2012). Black dots: locally detected seismicity by Hi-KNet (Hoste-Colomer et al., 2018). Note that the Xu et al. (2017) profile is offset by ∼75 km to the west, and has been processed differently than our profile, but we juxtaposed it properly to our image using their station-wise Moho depth estimates (green crosses based on differential delay times of Ps and PpPs Moho-phases from station-stacked P-RFs). Their thick black dashed lines: interpretation of the Moho and an intra-crustal discontinuity. Their green dashed line: top of another type of LVZ that are characteristic of southern Tibet and not discussed here. (b) Interpretive sketch showing the configuration of the underthrusting Indian plate beneath the Himalayas and the Tibetan plateau. Our observations of the Moho and MHT are represented in red solid lines, and the extrapolations of the MHT in red dashed lines. LVZ: low-velocity zone. Dashed black line on the right side indicates the intra-crustal discontinuity as drawn by Xu et al. (2017). White arrows represent motion of the India plate relative to Tibet. Fault name abbreviations as in Figure 2.1.*

cannot conclude on these aspects due to incomplete back-azimuthal coverage (Fig. S2[1]). In the absence of reliable information and coherent signal on dip and anisotropy across our array, we assume that the negative-over-positive features are caused by the top and the bottom of an LVZ. Furthermore, the fact that this LVZ is observed on both profiles (Figs. S5[1], S6[1]) and also elsewhere in the Himalaya (see below) corroborates our interpretation and indicates that the LVZ is pervasive along-strike of the orogen.

## 2.5 Interpretation and discussion

Our interpretation is based on the most robust results revealed by RF imaging (Figs. 2.2, 2.3). The Moho geometry connects well with the one derived from P-wave RFs in southern Tibet (Xu et al., 2017), with discrepancies of less than 5 km at their southernmost stations, reasonable for lateral variation over the ∼75 km distance separating the two profiles.

In Western Nepal, the distance over which the Moho reaches its maximum depth differs from Central Nepal (Fig. 2.4, Nábělek et al., 2009): the gentler descent ends further north, north of the Higher Himalaya, at nearly 80 km depth beneath southern Tibet (Xu et al., 2017). This may reflect a slightly different flexural rigidity of the India plate in Western Nepal compared to Central Nepal, although there is no significant difference in flexure West and East of our profile in Nepal as seen by gravity anomalies and numerical modelling (Berthet et al., 2013), unlike further towards NW India and to the Eastern Himalaya (Lyon-Caen and Molnar, 1985; Hammer et al., 2013; Hetényi et al., 2016b).
In comparison to other profiles across the Himalayas (Fig. 2.4), our Moho depth is different by up to 5 km than that observed in Central Nepal at longitude 85°E (Nábělek et al., 2009). It is also 10 - 15 km deeper than in Garhwal Himalaya at longitude 79°E (Caldwell et al., 2013), but 10 - 15 km shallower than beneath a sparse profile in the NW Indian Himalaya at longitude 77°E (Rai et al., 2006). While the general appearance and shape of the Moho in Western Nepal is to the first order similar to other profiles across the Himalaya, there are clear long-wavelength lateral variations along-strike of the orogen (Fig. 2.4). Although some of these stem from variable processing of seismological data (mostly CCP migration of RFs, but with different velocity models) in different papers and uneven data coverage, the shown variability can contain true structural elements that reflect inherited structure of the India plate entering the collision zone (Hetényi et al., 2016b).
The low-velocity zone identified from clear negative-over-positive amplitudes (Figs. 2.2, 2.3) along a ∼55 km long segment is similar to the one observed in Central Nepal (Duputel et al., 2016; Nábělek et al., 2009) although we observe it ∼15 km further north, more distant from the Main Frontal Thrust. Our imaged LVZ agrees with similar features beneath the Satluj valley, northwest Himalaya (Hazarika et al., 2017). Regarding earlier suggestions of dip and/or anisotropy to cause this mid-crustal signal, we cannot make strong statements as our dataset lacks the necessary back-azimuthal coverage (Fig. S2[1]) and there is no lateral coherency of the signal. Therefore, and by analogy to other parts of the Himalaya, we

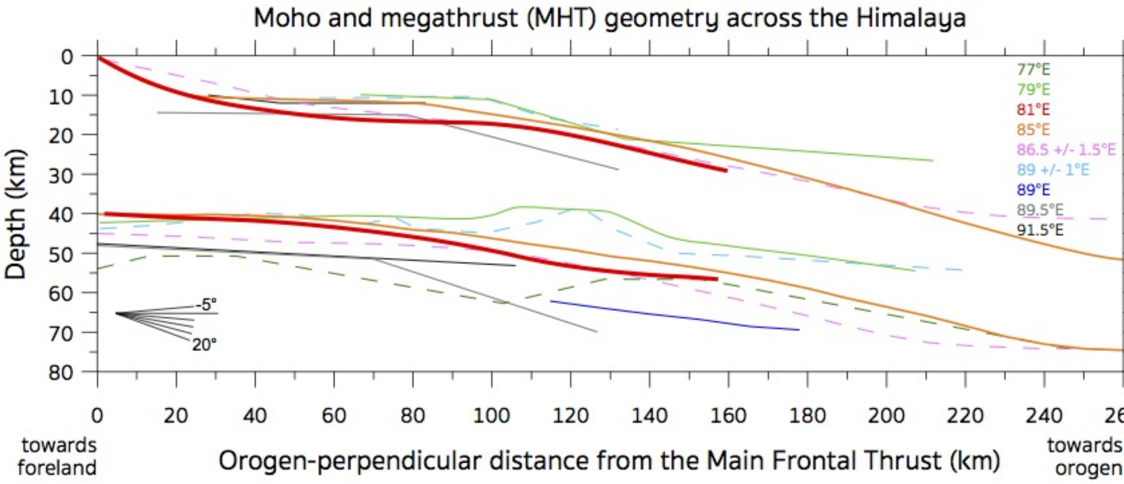


**Figure 2.4:** *Along-strike comparison of Moho and MHT geometry across the Himalayan orogen. The information are taken from profiles at 77°E (Rai et al., 2006), 79°E (Caldwell et al., 2013), 81°E (this study), 85°E (Hetényi, 2007), 86.5±1.5°E (Schulte-Pelkum et al., 2005), 89±1°E (Acton et al., 2011), 89°E (Hauck et al., 1998), 89.5°E and 91.5°E (Singer et al., 2017). The drawing of the 77°E, the 79°E and the 89±1°E profiles are adapted from Caldwell et al. (2013)'s figure. To account for proper projection, all other profiles are freshly redrawn to scale. Profiles with sparse data or wider lateral smoothing are shown in dashed lines. All these results stem from receiver-function analysis, except for the 89°E profile which is from active seismics.*

interpret this feature as a seismic low-velocity zone, due to the local accumulation of fluids originating from metamorphic dehydration reactions of the sediments underthrusted beneath the MHT. Indeed, the analysis of fluid inclusions of quartz exudates sampled within the MCT shear zone – which is a remnant of the MHT – demonstrates that both aqueous fluids (mainly brines) and $CO_2$-bearing inclusions, from metamorphic and meteoric origins, were injected from mid-crustal to shallower depths (e.g., Pecher, 1979). This result is consistent with the thermo-kinematic evolution of the Himalayan range (e.g., Bollinger et al., 2006). This geological observation is corroborated by the position in Central Nepal of a low-resistivity anomaly at mid-crustal depths, deciphered by magnetotelluric sounding, which also inferred the presence of fluids along the MHT's flat portion (Lemonnier et al., 1999). In Central Nepal, this same LVZ highlights position of the MHT along which rupture propagated during the 2015 Gorkha earthquake (Duputel et al., 2016). In NW India, beneath the Garhwal Himalaya, a similar interpretation is made by Caldwell et al. (2013). Therefore, we interpret the LVZ in Western Nepal as the position of the MHT, and draw the MHT at the central depth of the LVZ as Duputel et al. (2016) and other, earlier studies.

We also compare our results with the Chainpur and Simikot geological cross-sections from Robinson et al. (2006): the seismically imaged LVZ fits very well the position of geological MHT within uncertainties inherent to the methods. The depth of the LVZ's top corresponds to the depth of the lower décollement deduced from balanced cross-sections (Fig. 2.3a) while our interpretation for the MHT (central depth of the LVZ) is ∼3 km deeper. A locally steep ramp as the one at ∼65 km distance proposed from the geological cross-section could produce some of the transverse RF signal (Fig. S2[1]), but better station and back-azimuthal coverage would be needed to constrain it. Finally, this LVZ is matching perfectly the mid-crustal seismic cluster recently characterized in Western Nepal by our temporary network (Hoste-Colomer et al., 2018, Fig. 2.3), which suggests that the depth range around the megathrust is critically stressed.

Our images reveal a similar character but somewhat different depth of the MHT and of the Moho in Western Nepal compared to Central Nepal. On the scale of the orogen, long-wavelength along-strike variations are clearly present (Fig. 2.4). The transition between the mapped geometries along profiles could materialize in lateral ramps, also pointed to by seismicity studies in our study area (Hoste-Colomer et al., 2018), which may segment seismic ruptures laterally. Despite these variations, the overall similarity of the crustal geometries between Western and Central Nepal highlights a smoothly northward dipping flexural shape. This suggests that the boundary conditions to seismogenesis in Western Nepal are broadly the same as in Central Nepal. Therefore, the expected rupture characteristics and scenarios are also similar, suggesting that we can expect large (Mw>8) megathrust earthquakes in Western Nepal in the area where there has not been a major event since 1505 A.D.

## 2.6 Conclusions

This study, using data recorded by a two-year, temporary broadband seismological network in Western Nepal, and analyzed with the RF approach, allows us to conclude that:

- The Moho in Western Nepal is gently dipping northward, from a depth of ∼40 km beneath the foothills to ∼ 58 km beneath the Higher Himalaya, and then to nearly 80 km in southern Tibet (Fig. 2.3).
- A mid-crustal low-velocity zone is observed along ∼55 km distance, at ∼12 - 18 km depth, beneath the Lesser Himalaya (Figs. 2.2, 2.3). This LVZ is likely caused by fluids expelled from the underthrusting sedimentary rocks and trapped at the Main Himalayan Thrust. Our geophysical image is consistent with the depth of the MHT revealed by a geologically balanced cross-section (Robinson et al., 2006; Robinson and McQuarrie, 2012) and a mid-crustal seismic cluster (Fig. 2.3, after Hoste-Colomer et al., 2018).
- There are long-wavelength lateral variations in the depth of both the Moho and the MHT (Fig. 2.4). The presence of lateral ramps and lateral variations of the structures are hypothesized along or above the megathrust interface, structures that may influence or segment seismic ruptures along-strike of the orogen.

- The crustal configuration of Western Nepal is broadly similar to that in Central Nepal and the Garhwal Himalaya. Therefore, the processes of major earthquake generation should be alike, favoring scenarios of a megathrust event in the Western Nepal seismic gap that has not ruptured since 1505 A.D.

## 2.7 Acknowledgements

The seismological instruments deployed in Western Nepal in project Hi-KNet (http://dx.doi.org/10.15778/RESIF.ZO2014) belong to the French pool of portable seismic instruments Sismob-RESIF. We sincerely thank Roser Hoste-Colomer and the Hi-KNet team for data collection. We are grateful to the Nepalese Department of Mines and Geology for providing BHMN data and for supporting the installation of Hi-KNet. The Hi-KNet seismological data will be made available at http://seismology.resif.fr in June 2020.
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# Chapter 3

# Seismic Instrumentation

## 3.1 Brief overview of seismic sensors and their history

In this chapter I will give a short overview on seismic sensor and their history, to then discuss sensors adapted for educational purposes. Following a survey of possible sensors for our project, I present a number of physical tests for the shortlisted instruments. At the end, the Raspberry Shake 1D sensor is retained, for reasons explained at the end of this chapter.

### 3.1.1 Seismic sensors

A seismic sensor is an instrument to measure ground motion when it is moved by a disturbance. This motion is dynamic and the seismic sensor also has to record a dynamic physical variable related to the motion. There are several aspects which need to be handled while developing a sensor. As the sensor is typically installed at the Earth's surface and sometimes at a couple of meters depth, the ground would move with the shaking and there is no fixed reference available. According to the inertia principle, we can only observe the motion if it has an acceleration. Another aspect to consider is the amplitude and frequency range of the seismic sensors. The smallest motion of interest is the ground noise, which carries information and might be as small as 0.1 nm, and the largest motion could be on the meter scale (near a fault line during a great earthquake). Similarly, the frequency band starts as low as 0.00002 Hz (Earth tides) and could go to 1000 Hz. These values are of course the extremes, but a useful seismic station for local and global studies should at least cover the reasonable portion of this spectrum: a frequency band $\sim$ of roughly $0.01 - 100$ Hz and ground motions from 1 nm to 10 mm (Havskov and Alguacil, 2004).

**Passive sensors**: the most common sensor in seismology is the seismometer to measure the ground velocity during an earthquake. Since the measurements are done in a moving reference frame (the Earth's surface), almost all seismometers are based on the principle of inertia of a suspended mass, which will tend to remain stationary in response to the external motion. The relative motion between the suspended mass and the ground will then be a function of the ground's motion. Essentially, the seismometer consists of a swinging system with a signal coil that outputs a voltage linearly proportional to the ground velocity at frequencies above the natural frequency. The seismometer thus measures the relative ground displacement at high frequencies where its frequency response is flat. These sensors are more suitable for weak motions.

**Active sensors** measure acceleration which is proportional to the force applied to an object that causes it to change its position. These sensors are mostly based on the force-balance principle, meaning that the external force on the sensor mass is compensated by an electronically generated force in the opposite direction so that the mass remains stationary (also true for some velocity-meters). The force is generated by a current through a coil and measuring the current explains the external acceleration directly. Hence, an accelerometer gives information about the force that an object experiences during earthquake shaking. Active sensors are suitable to measure strong motions.

Traditionally, seismologists prefer recording weak motion displacement or velocity, for easy interpretation of seismic source and its behavior, while engineers and near-field seismology studies use strong-motion acceleration, whose peak values are directly related to seismic load on str uctures. For educational purposes, it is useful to demonstrate the principle of a seismometer with moving parts, so that students or the general public can see how an external excitation results in physical motion and recordings.

### 3.1.2 Seismometer development history

It is widely accepted that a Chinese astronomer, Zhang Heng, had built a seismometer in 132 A.D. based on the model of a jar-shaped instrument using dragons, toads and a ball. This is the earliest known seismometer, which was able to record shaking beyond a certain threshold level, and record the principal direction of first motion. Then, there were a lot of approaches for the development of seismometers around the globe, applying different theories but mainly a simple pendulum mechanism. Even though several efforts have been applied from the 13th to 19th century to record the Earth's motion, even in the late 19th century these remained largely individual efforts. Seismic sensor development has accelerated with the advent of seismology after the 1906 earthquake in San Francisco.

The Wood–Anderson seismograph was developed in 1922 (Anderson and Wood, 1925) and the earthquake Richter-magnitude scale is based on its records (Richter, 1935). It was an electromagnetic seismometer with galvanometer-photo paper recording, and an updated version (Lehner, 1959) was stable enough to deploy for the Worldwide Standardized Seismograph Network (WWSSN) (Oliver and Murphy, 1971). Different seismometers were tested after 1922, however, they remained experimental as inconvenient for routine work. The time between 1960 and 1975 was the period of transition from electromagnetic to electronic seismometers. The first digital broadband seismometer was operated at the California Institute of Technology, United States as early as 1962 (Miller, 1963) with the intention to preserve the greatest spectrum, dynamic range, and sensitivity. Nevertheless, its installation was discontinued because of the unfit digital technology at the time. The first practically successful digital broadband seismometer has been operational since 1976 in Germany (Buttkus, 1986). The present generation of digital very-broad-band seismometers covering the full teleseismic bandwidth including the free-mode band was developed in 1984 (Wielandt and Steim, 1986). The advanced technology enables to have more sensitive seismometers, and as of today there are many well-developed seismometers available in the world for different purposes. Without aiming to be complete, the timeline of seismometer development is presented in Table 3.1.

| **Year** | **Name** | **Remarks** |
|---|---|---|
| 132 | Zhang Heng (China) | Dragons,toads and a ball; minimum intensity and direction measurement |
| 1707 | De la Haute-Feuille (France) | Spilling over of mercury bowl |
| 1731 | Nicola Cirillo (Italy) | Simple pendulum observation of amplitudes |
| 1751 | Andrea Bina (Italy) | Simple pendulum above tray of sand |
| 1783 | Nicola Zupo (Italy) | Common pendulum |
| 1784 | Atanasio Cavalli (Italy) | Re-invented the 1707 mercury-filled-bowl seismoscope |
| 1792 | Borda (France) | Wire pendulum for gravity observations |
| 1796 | Duca de la Torre (Italy) | Common pendulum with timing device |
| 1844 | Forbes (Scotland) | Inverted-pendulum seismometer, ground displacement record due to long period of pendulum |
| 1834 | Luigi Pagani (Italy) | Vertical pendulum |
| 1856 | Luigi Palmieri (Italy) | Collection of seismoscopes for measuring different parameters, later to be used in Japan and California |
| 1857 | Cavalleri (Italy) | Electromagnetic seismometer |
| 1869 | Zöllner (Germany) | First horizontal pendulum, constructed to detect gravitational changes. The principle of the Zöllner-suspension was later used by Galitzin (1914), Wood-Anderson (1922) and Sprengnether (1940). |

| **Year** | **Name** | **Remarks** |
|---|---|---|
| 1875 | Cecchi (Italy) | Seismograph which recorded the relative motion of the pendulum and the time. Recorded the Menton earthquake on February 23, 1887. |
| 1880 | Ewing (Japan) | Common-pendulum seismograph |
| 1882 | Gray, Ewing (U.K.) | First vertical seismograph |
| 1889 | Rebeur-Paschwitz (Germany) | Observes distant earthquake with astronomic vertical pendulum, which was similar to Ewing's pendulum (1880) |
| 1893 | Cancani (Italy) | 7 meter common pendulum seismograph, distinguished P- and S-waves |
| 1895 | Giovanni Agamennone (Italy) | Electric seismoscope |
| 1895 | John Milne (U.K.) | Pendulum seismometer |
| 1897 | Milne | Suggests world-wide network of seismographic stations with standard instrument (realized in the 1960's only) |
| 1899 | Omori (Japan) | Seismograph with magnification of 10, natural period 20 seconds, basis for Bosch-Omori seismograph built later in Strasbourg |
| 1899 | Milne | First travel-time tables of P-waves |
| 1900 | Oldham (U.K.) | First travel-time tables of S-waves |
| 1900 | Schlüter (Germany) | First long-period vertical seismograph, magnification = 160, period = 16 seconds, photographic record |
| 1903 | Emil Wiechert (Germany) | Horizontal seismometer |
| 1903 | Galitzin (Russia) | Electromagnetic seismograph, based on ideas on seismoscopes and galvanometers |
| 1909 | Bosch-Omori | Large horizontal pendulum for observation of distant earthquakes, mass = 25 kg period = 15-20 seconds |

| Year | Name | Remarks |
|---|---|---|
| 1910 | Conrad (Austria) | Small horizontal pendulum for the observation of local earthquakes |
| 1922 | Wood-Anderson (U.S.A.) | Torsion seismograph (not electromagnetic), period = 0.8 seconds, magnification = 2800, and period = 6 seconds, magnification = 800. |
| 1926 | de Quervain, Piccard (Switzerland) | First force-feedback system which compensates mass movement, 21-ton seismograph |
| 1934 | LaCoste (U.S.A.) | long-period vertical seismometer |
| 1935 | Charles Richter (U.S.A.) | Develops the Richter magnitude scale based on the Wood-Anderson seismograph. |
| 1964 | WWSSN installed | Digital global network |
| 1969-1971 | HGLP | High Gain Long Period digital instruments distributed by Columbia University, in Alaska, Australia, Israel, Spain and Thailand. First stations to resolve Earth's noise in the 20 - 100 second period range. |
| 1973 | force-feedback for broadband sensors | From here all broad-band sensors incorporate the force-feedback principle. |
| 1977-1987 | LaCoste-Romberg | Force-feedback gravimeters are used for recording free oscillations of the Earth |
| 1982 | Wielandt, Streckeisen | STS-1 sensors are deployed under the GEOSCOPE project |
| 1984 | Wielandt, Steim | high-dynamic-range (>140 dB) seismic sensor, very broad-band seismograph Quanterra |
| 1990 | Wielandt, Steim, Streckeisen | Q680-family (Quanterra's low power, 6-channel 24-bit with 80 Hz sampling and remote data access) with STS-2 wide bandwidth sensors by Streckeisen |

**Table 3.1:** *Seismometer development history until 1990. (Sources: Dewey and Byerly, 1969; RING, 1992; Scherbaum, 2013)*

## 3.2 Seismometers for educational purposes

Apart from the research perspective, seismometers can also be useful for educational purposes and earthquake signals can now easily be measured in classrooms around the world using educational seismometers. As for research instruments, various educational instruments were developed through time, with the objective of a functional device for student use in understanding earthquakes and ground motion recording. These often record shorter-period signals but are easier to handle, therefore they are perfectly suited for the classroom environment. More recently, digital devices became widespread (e.g., Cochran et al., 2009), and some educational seismic networks spread over larger regions (see Chapter 1.3). In this section a few of seismometers adapted for education purposes are presented.

### 3.2.1 Quake Catcher Network

Recent advances in micro-electro-mechanical systems (MEMS) sensing and distributed computing techniques have enabled the development of low-cost, rapidly deployed, dense seismic networks like the Quake-Catcher Network (QCN) to detect vibrations of seismic waves (Cochran et al., 2009). The QCN sensor uses tri-axial MEMS accelerometers to record moderate to large earthquakes. MEMS accelerometers are simply microchips with a very small set of force-balance cantilever beams inside. The balance mass weight is compensated by low-level electrical voltage.

The QCN includes a series of sensor types, some embedded in devices such as laptops, and some are connected to computers via USB connections, therefore the QCN is a potential candidate to provide critical earthquake information by filling in the gaps between traditional seismic stations. The QCN sensors measure accelerations between -2g and +2g.

The QCN has started in the USA and then has expanded for creating a global strong-motion seismic network to improve earthquake monitoring, earthquake awareness, and the science of earthquakes in high schools. The QCN needs additional computing platform, the Berkeley Open Infrastructure for Network Computing (Anderson, 2004). The QCN has also developed educational software, QCNLive, for learning using the sensors and lesson plans to teach about earthquake vibrations and where earthquakes occur. The QCN has been so successful that it has inspired and provided the basis for the development of other similar programs.

Approximately 2'000 QCN sensors were running around the world in 2013, densely distributed in the United States and Europe (Fig.3.1). As QCN sensors record strong motion, several temporary networks were created just after a big event in the shaken areas to record the aftershock sequences, for example, following two big events in 2010, the M8.8 in Chile (Lawrence et al., 2011) and the M7.1 in New Zealand (Cochran et al., 2012), as well as the 2015 M7.8 Gorkha earthquake in Nepal (Dixit et al., 2015). The sensitivity of the QCN sensors is lower than that of traditional and research sensors, but still good enough to record moderate to large earthquakes (e.g., $M > 5.0$, see Fig. 3.2).

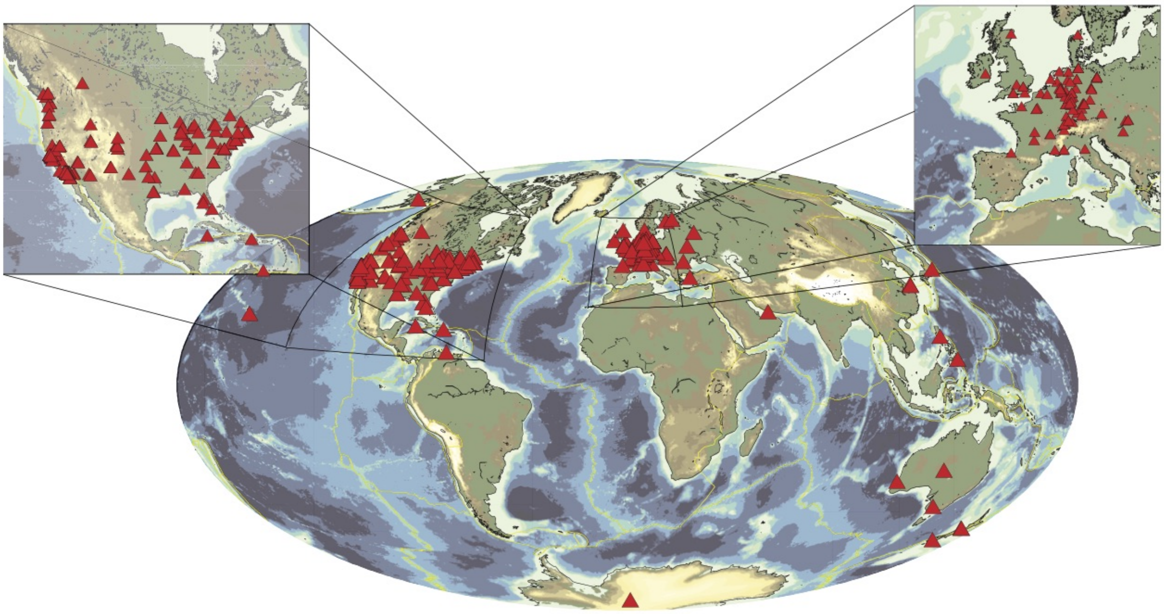

**Figure 3.1:** *Global Distribution of QCN Stations. QCN laptop-sensor locations (red triangles) as of April 2008 on a global topography map. Maps of North America and Europe show a higher density of sensors. The symbols for many locations overlap in metropolitan areas. Source: Cochran et al. (2009)*

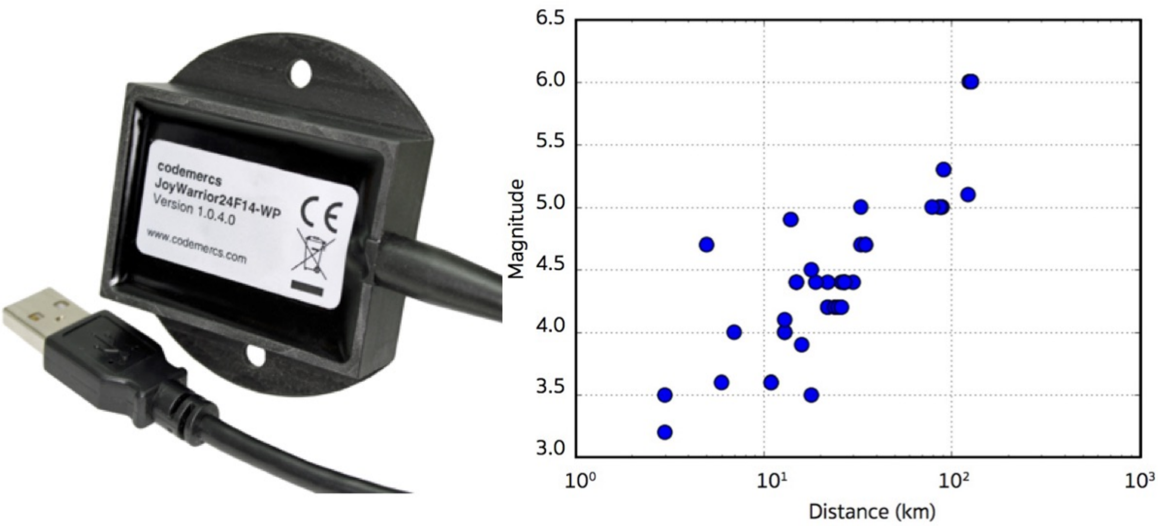


**Figure 3.2:** *Left: Quake-Catcher Network JayWarrior24F14-WP model. Right: Magnitude vs. distance plot for earthquakes recorded by the QCN in Greece. The QCN sensor is able to detect a M3.5 earthquake within 10 km, or a M4.0 within 30 km. This figure gives a good indication of the detection capacity of these sensors. Source: Bossu. (2016)*

However, to use QCN sensors for education purposes, there are some limitations. It requires a desktop PC running continuously. The QCN sensors are accelerometers and therefore they cannot record small earthquakes or large remote earthquakes, but only strong ground motions. Even in earthquake-prone regions, they record too few earthquakes to attract students' attention regularly. Time synchronization problems occur frequently and make QCN data unusable. The main disadvantages of this sensor are that it is a black-box sensor, without pedagogical value, and that data recording is triggered and therefore continuous data is not available for studying other phenomena. Finally, we could not consider QCN sensors as they are no longer available on the market and also the program coordination seems to have stopped.

### 3.2.2 Slinky seismometer

The slinky is a vertical seismometer designed with coil and a magnet suspended on a long spring, providing a simple, low-cost solution to earthquake detection. The seismometer uses electromagnetic induction to detect ground motion and incorporates eddy current damping for improved sensing. The educational value is high as it can very well demonstrate the principle to students. However, it requires a suitable digitizer, a waveform displaying software (such as the most common jAmaSeis), and it is inconvenient to travel with. Further details and a picture are provided in Chapter 4.

### 3.2.3 SEP seismometer

The science enhancement program (SEP) seismometer system was designed to be compatible with the existing jAmaSeis seismic data logging and analysis software, and was launched in 2007 together with a tried and tested set of classroom science activities that all had seismology and earthquakes (Denton, 2008a). This is a horizontal seismometer that uses electromagnetic induction and force of inertia to detect ground motion. In the case of the SEP seismometer, there is a large mass at the end of a boom, and this boom is able to swing from side to side (Fig. 3.3). This is a very good instrument for education purposes, but might be inefficient to record small earthquakes. Also, it takes a more serious work for installation and calibration.

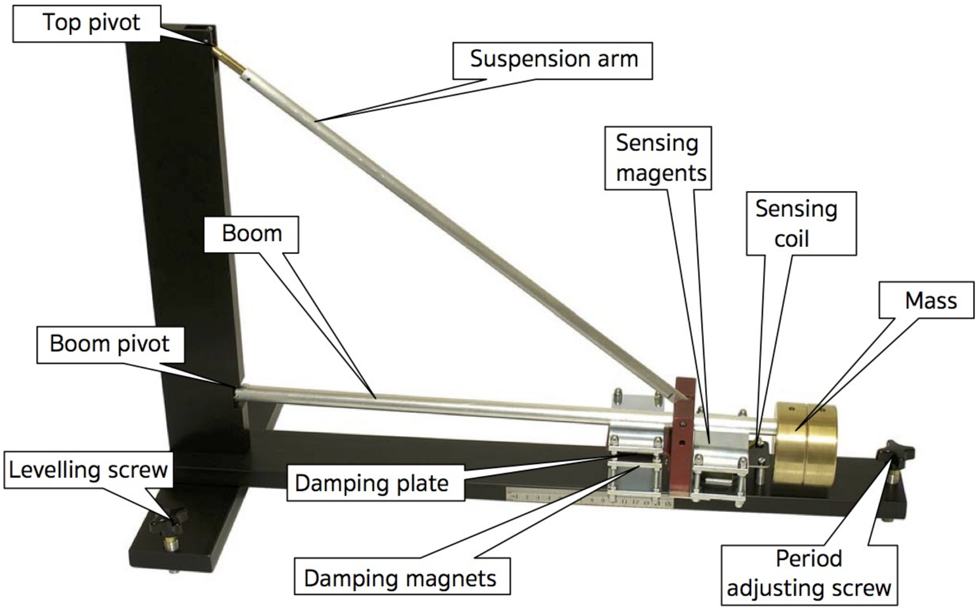


**Figure 3.3:** *SEP seismometer with labelling of each element. Source: Mindsets (2018).*

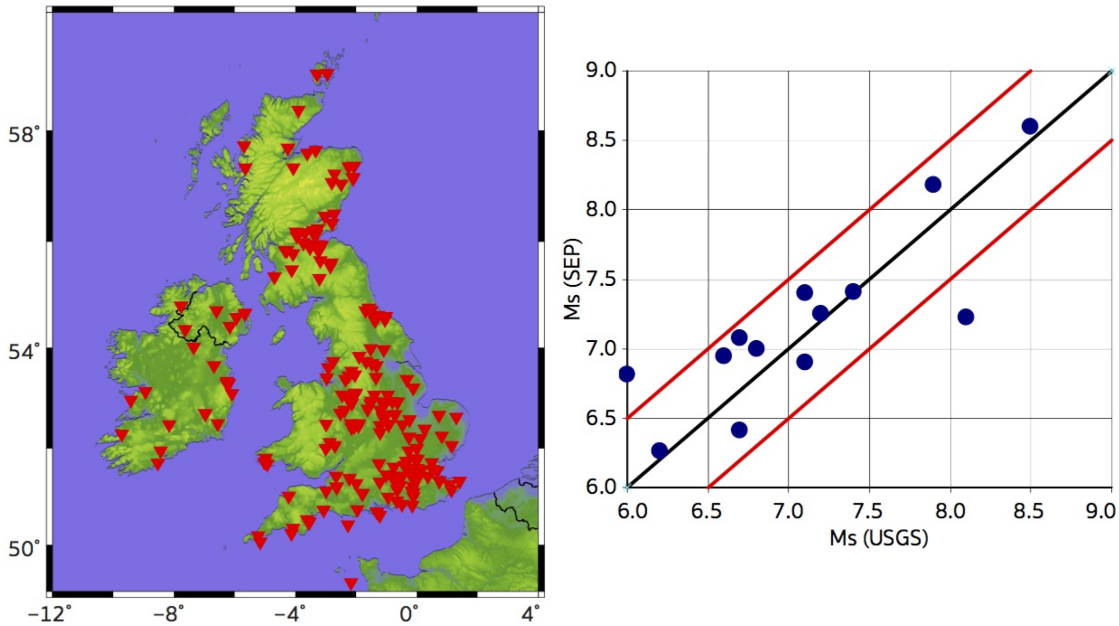


**Figure 3.4:** *Left: SEP seismometer map installed in Ireland and in the United Kingdom. Right: Magnitude comparison of SEP and USGS solutions for strong earthquakes. Source: Mindsets (2018).*

The SEP seismometer system is currently used by the UK school seismology program and the Seismology in school network in Ireland (Fig. 3.4, left), as well as the Romanian educational seismic network (Tataru et al., 2016). The SEP is suitable to record strong earthquakes, and the computed magnitude from SEP seismometer data lies within 0.5 unit of USGS magnitudes (Fig. 3.4, right).

### 3.2.4 AS-1 seismometer

The AS-1 is an easy-to-use and effective seismometer for educational purposes, designed in 2000 in the USA to make the science of seismology accessible to individuals and schools at a reasonable cost. The AS-1 proved popular with teachers because of its simple and visually accessible design (Fig. 3.5, left).

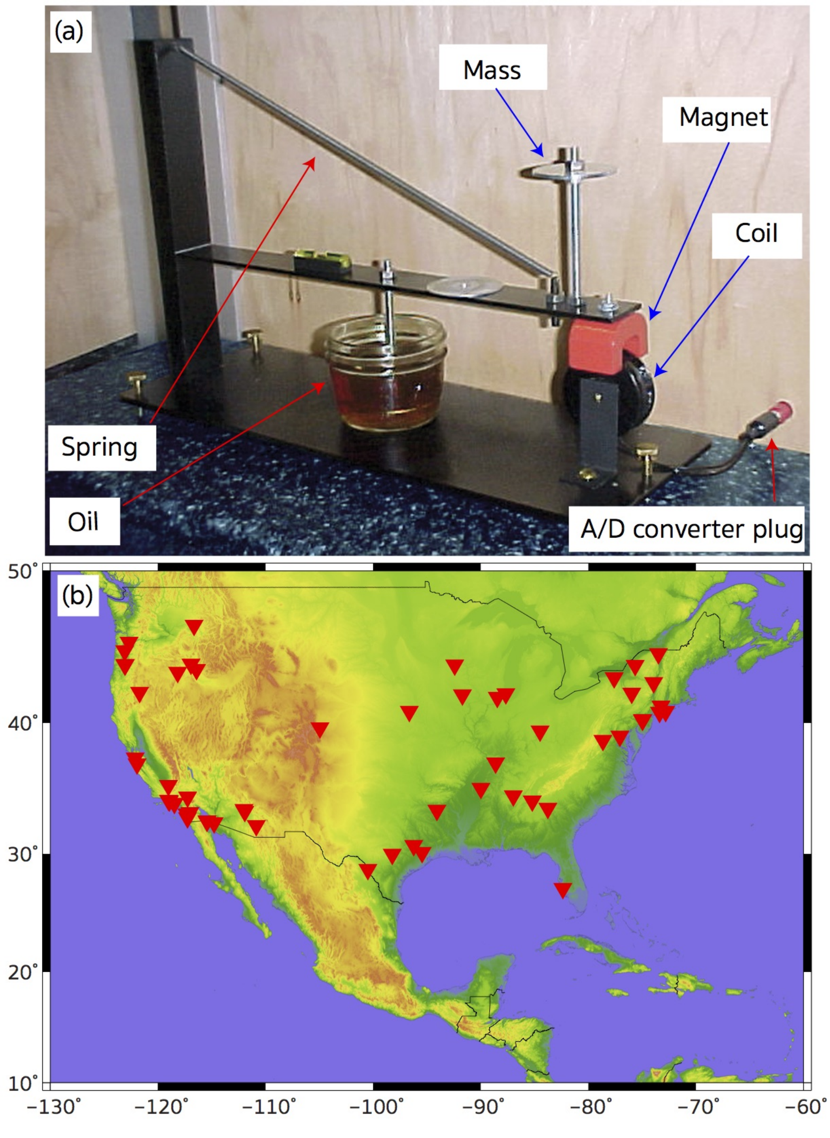


**Figure 3.5:** *(a) The AS-1 seismometer showing the main components of the instrument. (b) Map of the AS-1 educational seismic stations installed in US schools; this network is supported by IRIS education program.*

The AS-1 is a horizontal component seismometer. The mass of the seismometer, consisting primarily of the magnet, boom, and the washers, tends to remain steady because of inertia when the base moves. The motion of the coil relative to the magnet generates a small current in the coil. The current is amplified and digitized by an amplifier unit and connected to the computer for recording and display. It is combined with the waveform displaying software, mainly jAmaSeis, which allows real-time recording of seismic events and simplifies data analysis. This is the mainstay of a national seismographs-in-school programme in the USA, with over 200 schools running it with the help of Incorporated Research Institutions for Seismology (Fig. 3.5 right). The AS-1 seismometer records local quakes as small as magnitude 3.5 at a distance of 150 km and quakes magnitude 6.5 or larger that occur anywhere in the world[1]. This instrument is also suitable for education purposes, but installation could be difficult inside a school environment in a remote countryside.

## 3.3 Survey for instrument

Following a first look around the educational and low-cost seismometer market made me realize that the offer is broader than just a few instruments, and some criteria need to be set for a narrower selection to be tested for our educational seismology program in Nepal. Beyond the price, which must be suitable for a third-world country context, the bandwidth, the sensitivity, and the availability were the main points of interest. The results of my market survey, carried out in autumn 2017, is presented in Table 3.2. Out of these sensors, we have decided to purchase 4 different types: QCN, Lego, Slinky, and Raspberry Shake 1D instruments (see technical details in chapter 4 section 4). Among these, the QCN sensor could not be further tested as we could not retrieve continuous data and QCN support was discontinued. The three other sensors were subjected to detailed testing, the result of which are presented in section 3.5.

[1]The AS-1 installation and calibration details

| **Sensor Name** | **Descriptions** | **Price (USD)** |
|---|---|---|
| Quake Catcher kit | 3-component accelerometer. The official sensor of California University. External digitizer needed. | 44 |
| JoyWarrior 24F14 | Cost efficient, three axis acceleration and tilt sensor with USB interface. The USB interface allows for easy use with any computer. | 77 |
| Slinky | Educational Seismometer designed by the BGS in the UK. Requires a suitable digitizer. | 137 |
| Lego | Used for classroom demonstration. External USB digitizer required. | 210 |
| SISMOLO-Proto | A digital serial seismometer. The seismograms can be recorded into a computer. Product of a French Company. | 288 |
| TC-1 | Using scientific software, can record data directly in laptop. External digitizer needed. | 350 |
| Raspberry Shake 1D | A one component, improved geophone, digitizer and all components included, directly internet compatible. | 374 |
| Guralp educational | Single component seismometer. Made for the educational purpose. Colleagues suggested it is not very suitable for schools. | 500 |
| P-alert | Used in Greece for early warning purpose. Applicable for education purposes. | 500 |
| TS1 | slinky It demonstrated well how a seismometer works. Data can be recorded using additional software. Complaints on materials used to build. | 500 |
| SEP | Educational seismometer used in similar programs. External digitizer needed. | 531 |
| AS-1 | Similar as TC-1 seismometer. External digitizer needed. | 700 |
| Vibrato | Needs local network and power, includes a web server providing a full and easy access to the data recorded by the station. Product of French Company. | 1’774 |

| **Sensor Name** | **Descriptions** | **Price (USD)** |
|---|---|---|
| Guralp-EDU-V | Single component seismometer. Complete seismology package. Compact digitizer with 24-bit resolution. | 2'800 |
| Kelunji Gecko | Triaxial seismometer. Data records on SD card. | 4'130 |
| Guralp-6TD | Used for educational seismology in Australia. A research quality instrument, includes a digitizer. | 14'144 |

**Table 3.2:** *Initial survey results for low-cost seismometers, with main characteristics and price as of 2017.*

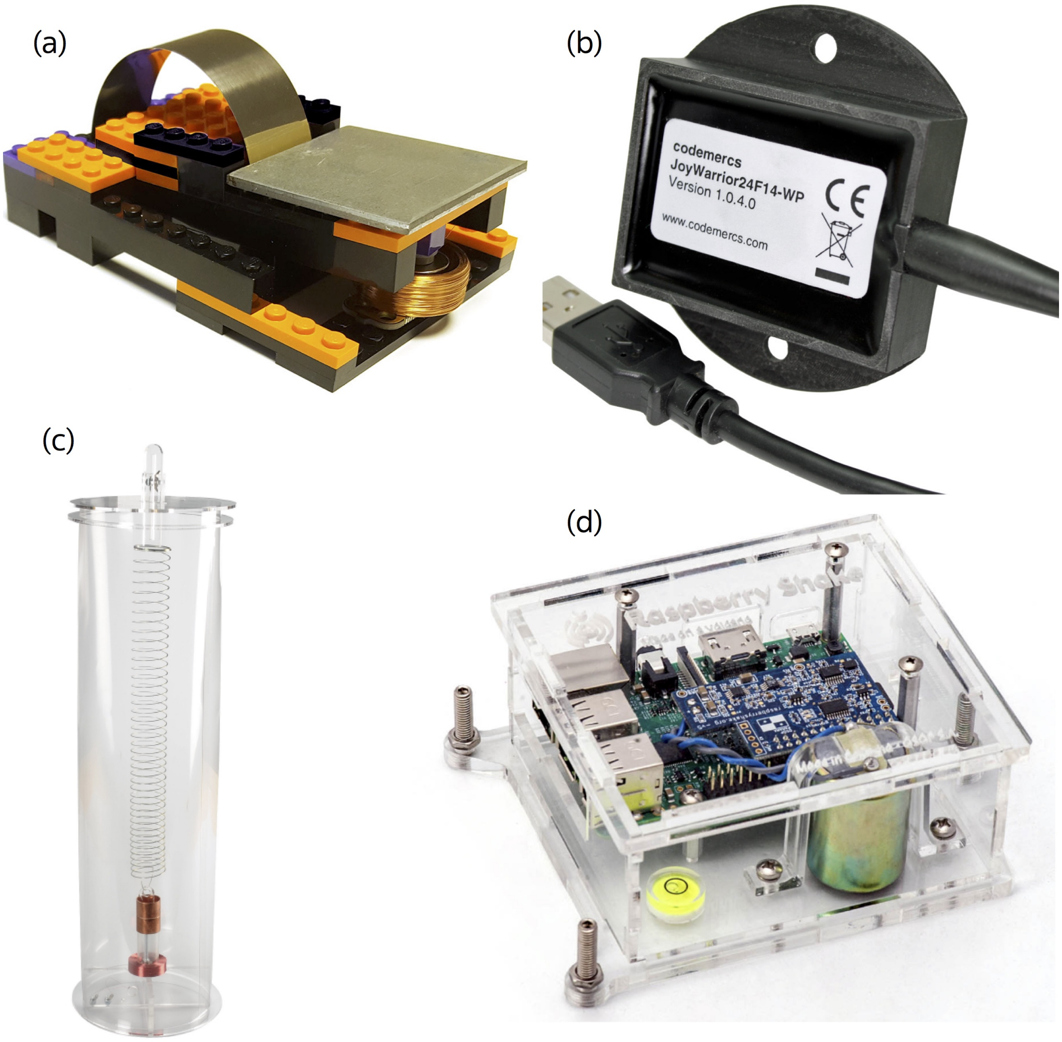


**Figure 3.6:** *Low-cost sensors purchased and tested before selecting one for our program: (a) Lego, (b) Quake Catcher, (c) Slinky, (d) Raspberry Shake 1D. See Table 4.2 for the characteristics of each sensor and our evaluation.*

## 3.4 Instrument testing

We purchased the selected four low-cost seismometer candidates to carry out physical test in order to assess their performance. The QCN sensor was discarded rapidly due to lack of continuous data availability and of support. We have then performed different tests for Lego (leaf spring), Slinky (analogue spring), and Raspberry Shake 1D (digital geophone) sensors in 'laboratory conditions', in the basement of the university building. A Raspberry Shake 1D (RS1D) seismometer has also been installed at a low-noise location in Grimisuat, canton of Valais, the region of highest seismic activity in Switzerland, to evaluate its performance with local earthquakes. Beyond the test presented in this section, chapter 4 (a published paper) gives an overview of these four sensors.

### 3.4.1 In-house tests

We do not own a true shake-table with controlled motion and parameters, therefore we have set up our "laboratory" to compare the sensors in equal conditions. We installed the three seismometers in a room in the basement of our university building, with no air conditioning, no machines in nearby rooms, and limited number of people passing by in the corridor. The goal was to observe and compare simultaneously recorded signals on the three sensors during jumping, walking, floor inclination, and the sensitivity to background noise.

**Noise**: Four hours of continuous data during day and at night are plotted for the three different sensors to see diurnal variations (Fig. 3.7a). The records from each sensor are clear, but in comparison, the Slinky and the RS1D are more sensitive and resolve the background noise more clearly (see counts on vertical scale on Fig. 3.7a). There are several peaks visible during the daytime which correspond to man-made activities. Cultural noise such as moving people, traffic and machinery activities are higher during the daytime, and hence we observe a noise level variation between day and night. The ratio of the signal's root-mean-square (RMS) between daytime to nighttime (4-hours) is approximately 1.55, 2.10 and 1.61 for Lego, Slinky and RS1D, respectively.

The largest peaks in the daytime records turned out the be vibrations caused by the bus (line 31) that strop in front of the building, at about 10-meter distance from the laboratory, on floor above the sensor location. The 15-minute schedule during a working day is clearly seen (Fig. 3.7a). We zoom to one bus stopping (Fig. 3.7b) and calculate the RMS ratio between the bus-signals (15 sec) and the background: it is estimated at ca. 3.18, 10.12 and 9.79 for Lego, Slinky and RS1D, respectively. Interestingly, the RS1D still records the bus stopping in a room that is 40 m away and has an anti-vibration floor for a high-precision geo-analytical facility.

**Jump, walk, bend**: Ground vibration following a person jumping at 1-meter distance is clearly recorded by each seismometer, and the signal-to-noise ratio is better for RS1D compared to Lego and Slinky (Fig. 3.8a). Smaller vibrations due to a person walking near

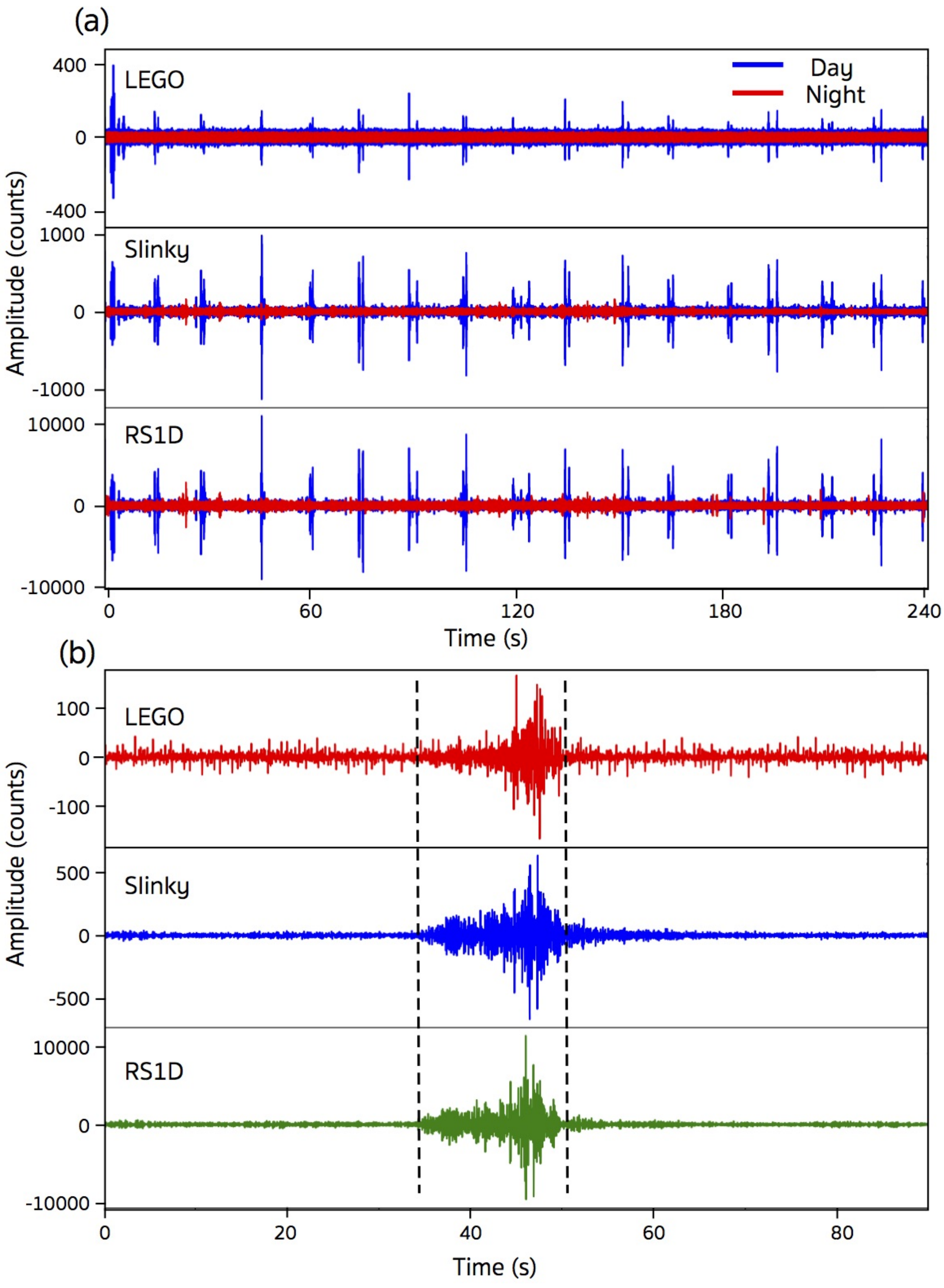


**Figure 3.7:** *(a) Typical daytime (blue) and nighttime (red) records. (b) Signal from a bus stopping at ∼ 10 m distance from the sensors.*

the sensors are also registered on all sensors (Fig. 3.8b). Finally, without moving a foot but changing on which leg is a person's weight the floor inclines; this test is carried out and is also detected by all instruments (Fig. 3.9a). The ratio of RMS for inclination-signals (50

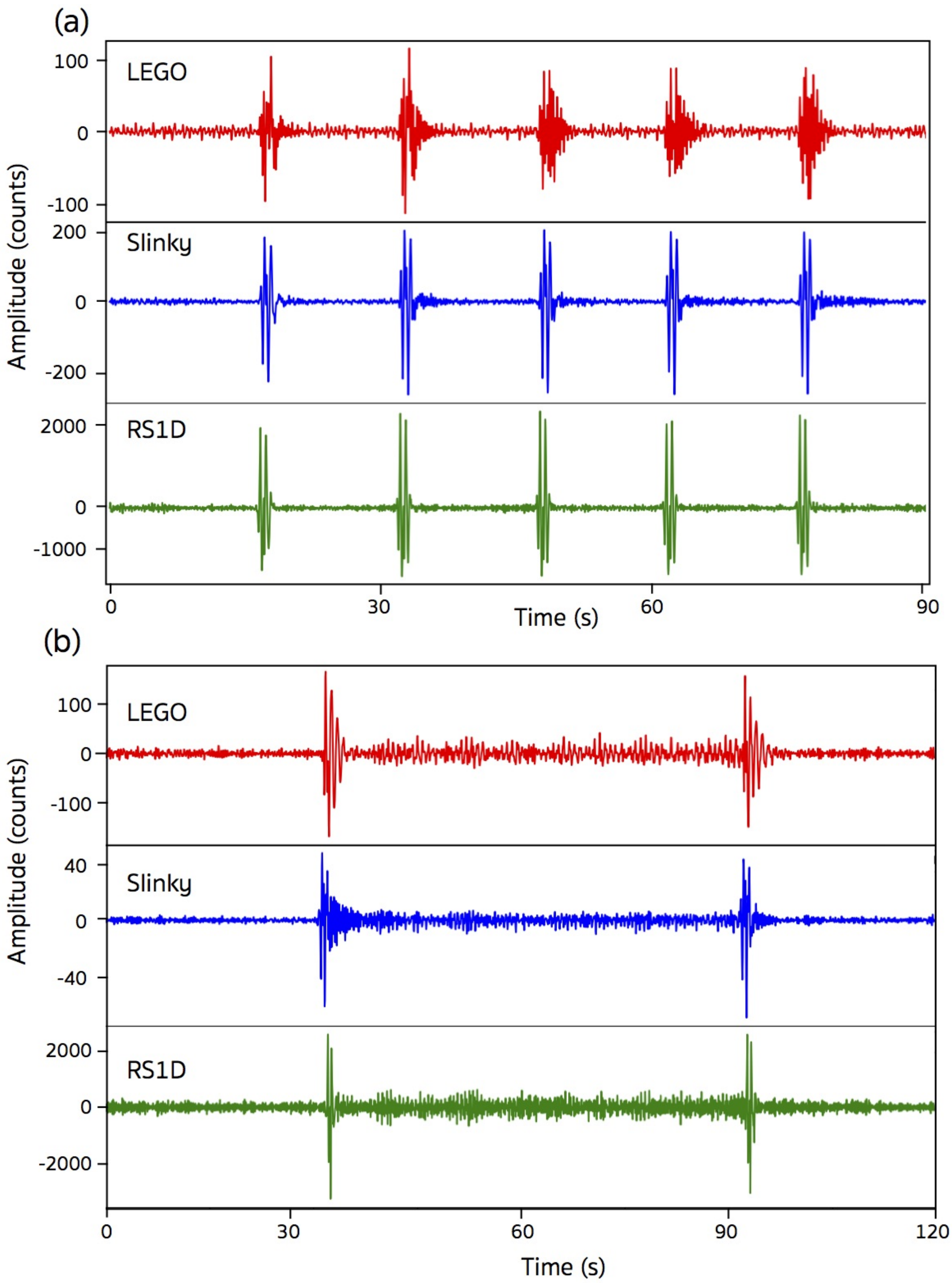


**Figure 3.8:** *(a) Jump test signals. (b) Jump and walking test signals.*

sec) and background signals is estimated at 5.21, 3.93 and 2.10 for Lego, Slinky and RS1D, respectively.

These test also allow to assess the damping parameter of each sensors, which is an important property of the instrument. This can be done by giving the mass an initial displacement,

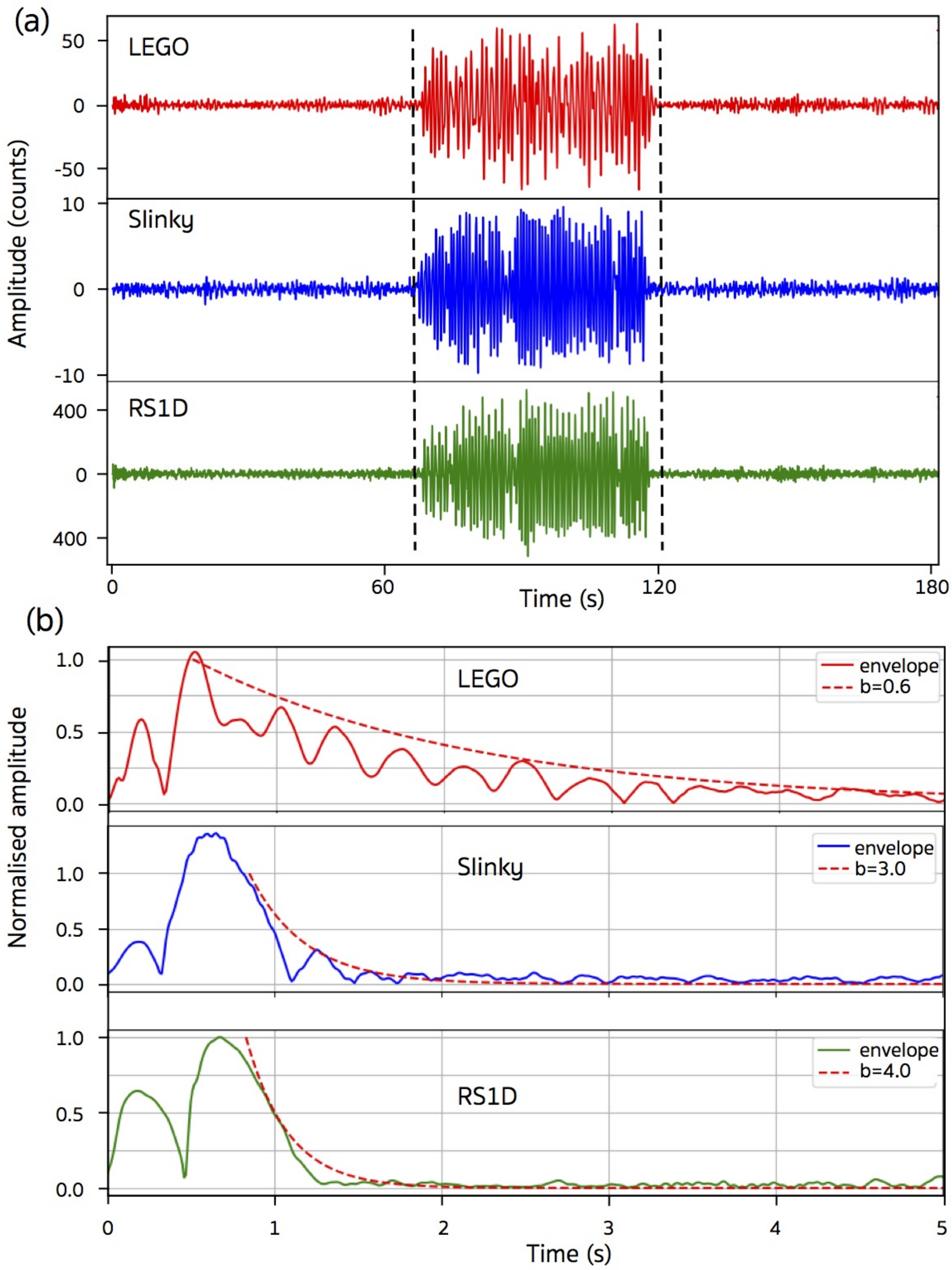


**Figure 3.9:** *(a) Inclination test signals. (b) Damping coefficient fit and computation.*

and see the gradual decrease of swinging. In Figure 3.9b, we have approximately fit the decaying normalized amplitudes by an exponential function with time. The observed damping coefficient for Lego, Slinky and RS1D are 0.6, 3.0 and 4.0 respectively, hence going from slow to fast decay in this order. The conclusion is that the Lego allows students to see the continuing effect of vibration for the longest time, so it is educationally useful, but to record local earthquakes the RS1D is most suitable. For a more precise test, the impulse response of each sensor should be obtained in controlled conditions, and with a time-wise narrow spike as input.

### 3.4.2 Field tests

#### 3.4.2.1 Natural seismicity

We installed one RS1D sensor (ID: R291C) in Grimisuat, as in our expectation many local earthquakes can be recorded in that area, provided the test site is quiet. This proved to be the case, as the house is little occupied and far from busy roads. We have observed clear earthquakes signals soon after installation, including a $M_L$ 1.0 event that occurred at 36 km distance on 2019-03-31T04:15:06 UTC according to the Swiss Seismological Service (SED). It's a promising result, and it is possibly the smallest earthquake recorded by an RS1D at that distance. Therefore, we were convinced that this seismic sensors is perfectly suitable for recording small earthquakes in Nepal in frame of our educational program, if the background noise is low. Some examples of recorded local earthquakes in Switzerland are presented in Figure 3.10.

#### 3.4.2.2 Foot-quakes

It is now a common observation that man-made vibrations such as sport event highlights can be recorded by sensitive seismometers. The detection depends on the crowd size, how synchronized is their motion, and the distance to the sensor. Our site in Grimisuat has recorded a so-called foot-quake, on April $7^{th}$, 2019. The wave was produced during the Swiss first league football game between Sion and Lucerne by the enthusiasm of the 8'900 fans present at the Stade de Tourbillon, Sion, following the earliest goal of the league scored by Ermir Lenjani, just 10 seconds into the game. Our sensor captured the waves at more than 2 kilometers from the stadium (Fig. 3.11 top, filter: 1 - 8 Hz).

Foot-quakes have been captured around the world. The ground-shaking caused when the Brentford fans celebrated a goal against Luton at Griffin Park stadium in the UK is recorded on November $30^{th}$ 2019 by a Raspberry Shake sensor (Fig 3.11 second panel, filter: 1 - 5 Hz). In the UK, some low-cost seismometers have been installed in schools and museums to record crowd induced vibrations, and clear signals were detected every time near the King Power Stadium when Leicester City scored a goal (Denton et al., 2018). The broadband seismometer installed in Barcelona has recorded up to 90'000 people celebrating as FC Barcelona defeated Bayern Munich in May 2015 in the Champions League semi-finals (Fig. 3.11 bottom, filter 1 - 6 Hz, from Díaz et al. (2017). Further clear ground shakings recorded during sport events include American football games (Michigan–Nebraska, 110'000 people, September $22^{nd}$ , 2018) and the 2018 football World Cup, where remote spectators in Mexico City celebrated a Mexican goal scored against Germany (Fig. 3.11 third panel, filter: 1 -

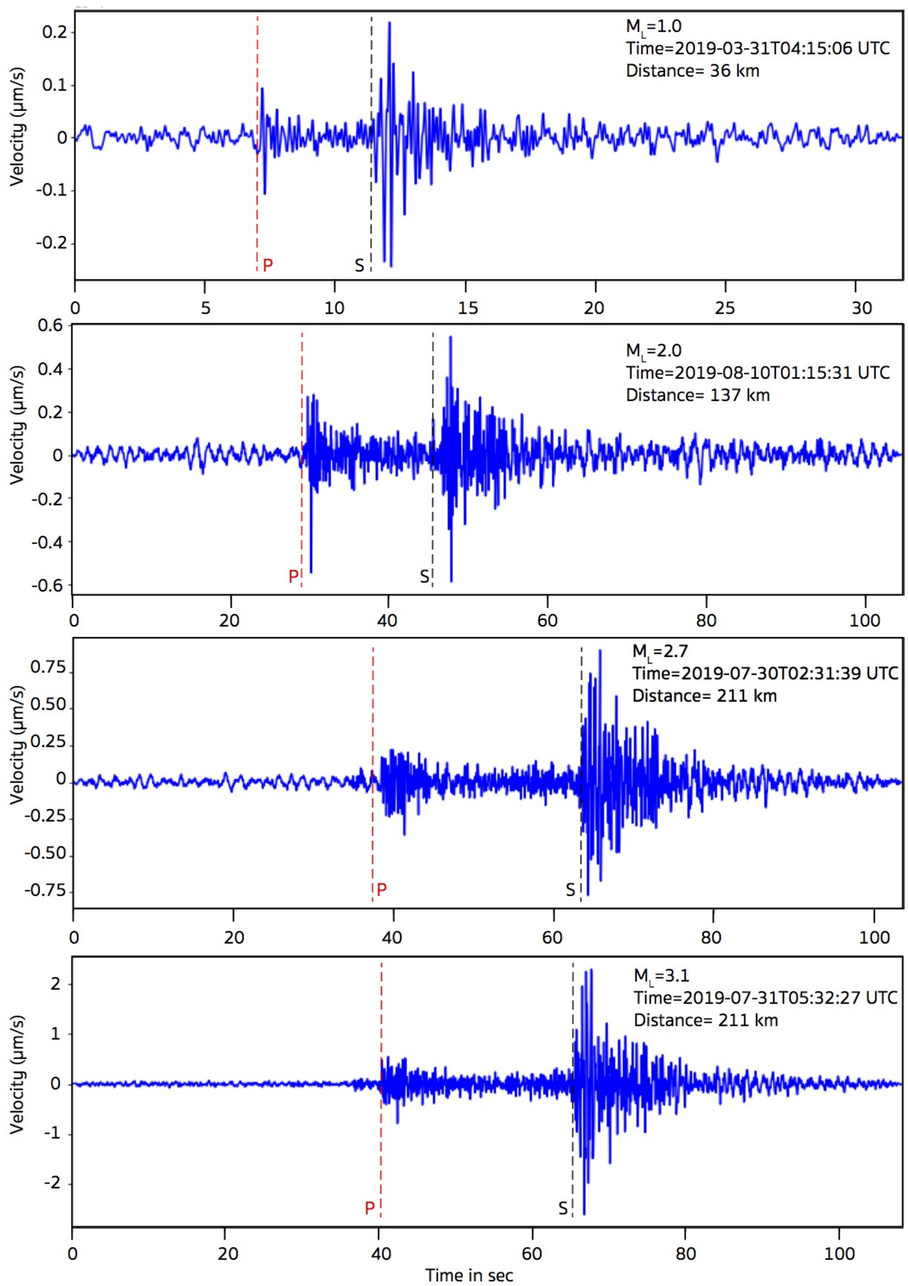


**Figure 3.10:** *Examples of earthquakes recorded at our test site in Grimisuat, Valais, Switzerland. The iasp91 velocity model's theoretical P-and S-wave arrival times are indicated by red and black dashed lines in each plot. Recorded signals are filtered in 0.7 - 7 Hz frequency band.*

8 Hz). In Fig 3.11, the foot quake record in Switzerland is 2 orders of magnitude smaller than the other records because the seismometer in Switzerland is far from the stadium but in other cases sensors are close to stadium or/and people's activity.

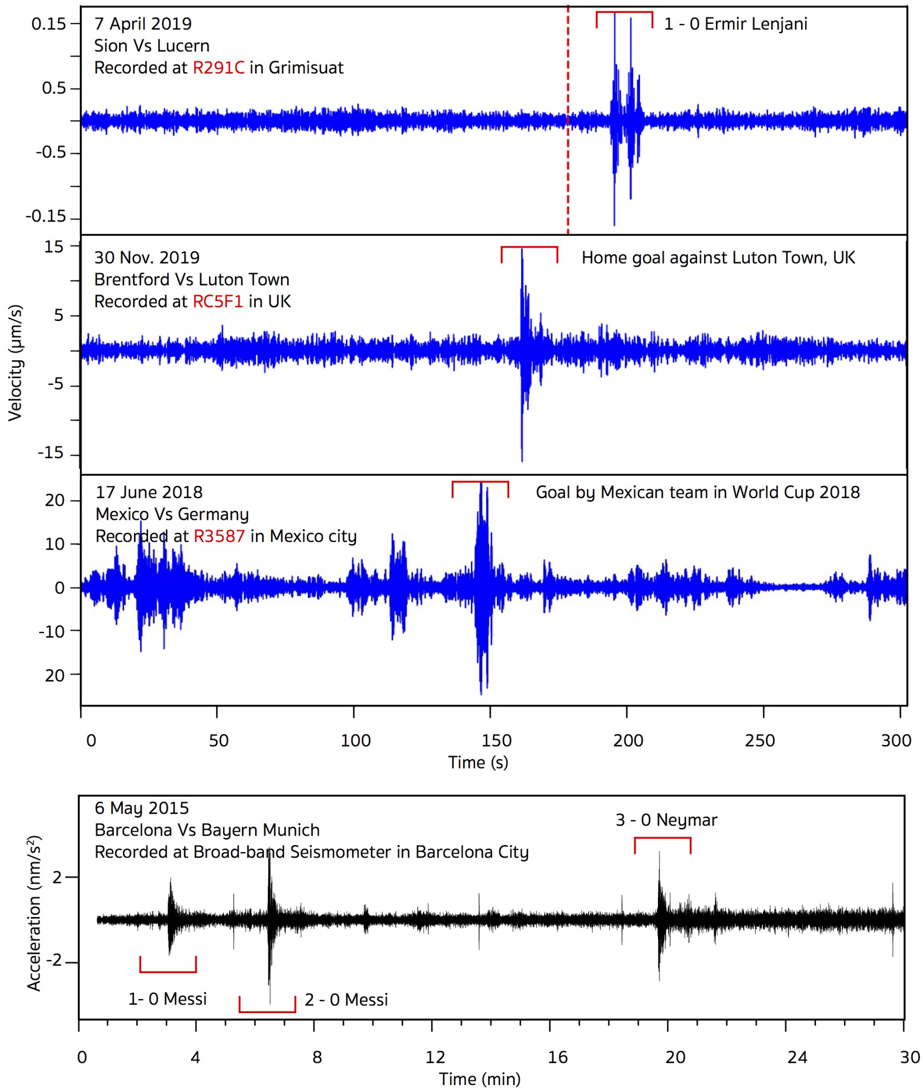


**Figure 3.11:** *Seismic records showing 'foot-quakes' in different countries. The top three plots are foot-quakes recorded by Raspberry Shake sensors, while the bottom plot is recorded by a broad-band seismometer. The red-dotted line in the top panel is the game start time. Vibration following goals are noted with respective information (see text for description).*

#### 3.4.2.3 Magnitude calibration equation

The most often asked question following an earthquake is to know its magnitude. To estimate this, several seismograms are required, and an equation relating ground motion to magnitude and distance needs to be established. Both our project in Nepal and our test site in Switzerland is recording earthquakes that are quantified by a local seismological agency. Therefore, our task is to adjust our procedures so that a magnitude can be estimated from our recordings, too. The idea is to fit our own observed $PGV_V$ to the existing local magnitude from the published catalogue. The procedure to do so is explained in detail in chapter 4, for the Nepal case, including the basic considerations to the final equations. Here, for the Valais station, we only document the main steps, and refer to chapter 4 for details.

In a first step, we collect peak ground velocity $PGV_V$ (subscript V for vertical component record) information at our site following earthquakes communicated by the SED, and plot them as a function of published distance D and published magnitude M. We can clearly see that $PGV_V$ decreases with distance and increases with magnitude (Fig. 3.12), and therefore aim to fit an equation of the following form (based on Allen et al., 2012):

$$log_{10}(PGV_V) = a + b \times M_{TEST\_SITE} + c \times log_{10}(D) \tag{3.1}$$

We then keep events in the 6 - 290 km distance range and $M_L \leq 3.4$ to sufficiently populate 0.1 unit wide magnitude bins, and regress for the intermediate distance attenuation value c (Fig. 3.13a). The $1\sigma$ trimmed median determines $c$, based on which the value of $a$ and $b$ can be regressed (Fig. 3.13b), and this produces a set of lines fitting our data (Fig. 3.12).

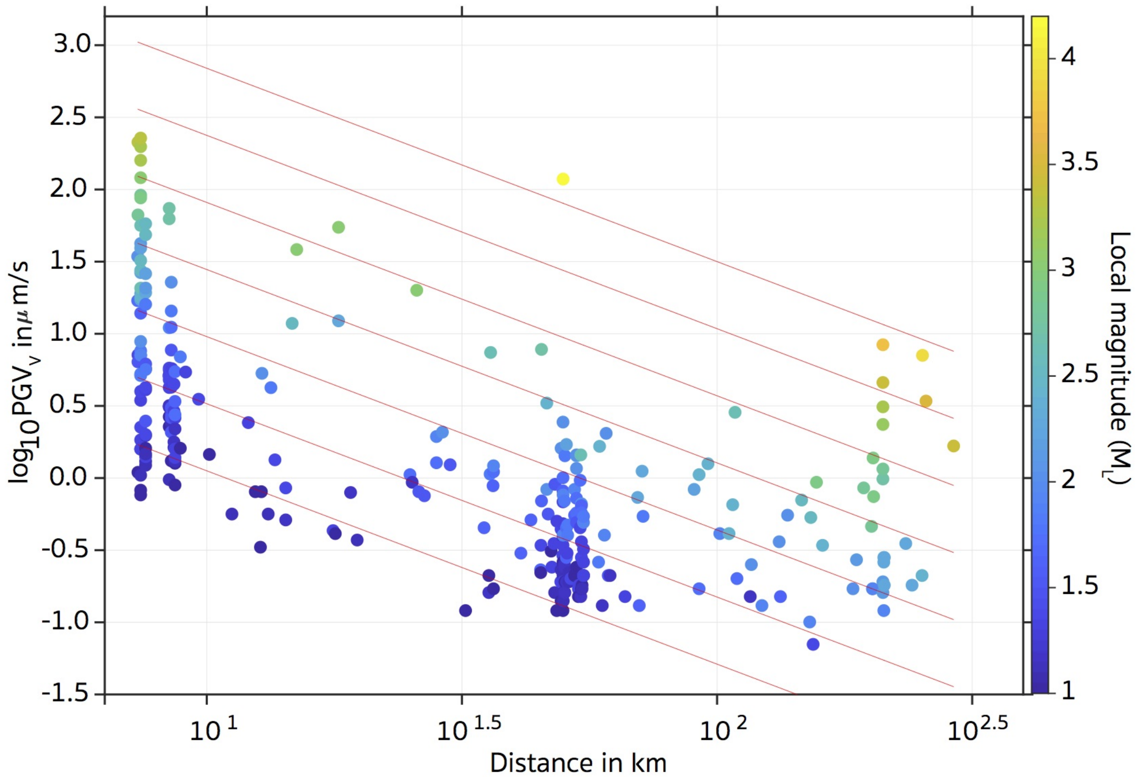


**Figure 3.12:** *Observed peak ground velocity ($PGV_V$) at test site in Grimisuat, Switzerland as a function of earthquake magnitude and epicentral distance. Each circle in the plot represents a single earthquake detection at the station, colored by magnitude. One-year data are considered from April 2019. Source of earthquake data is the Swiss Seismological Service's published catalogue. Red lines represent the fitted $PGV_V$−distance lines for M1.0, M1.5, M2.0, M2.5, M3.0, M3.5 and M4.0 earthquakes after the regression.*

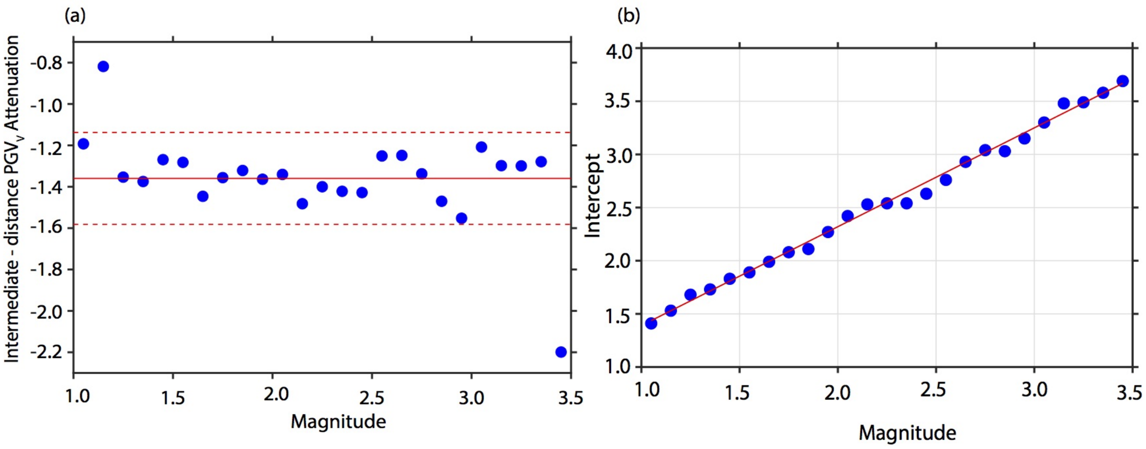


**Figure 3.13:** *(a) Intermediate distance $PGV_V$ attenuation c plotted for magnitude bins. Data points beyond the $1\sigma$ variability (0.22, red dashed lines) of the raw mean ($-1.36$, solid red line) are trimmed, and the median of the remaining values provided parameter c to be $-1.34$ across the dataset. (b) Fitting the distance and $PGV_V$ data for each magnitude window using the constant slope value c to find the slope and intercept of the magnitude dependence (respectively b and a in Eq. 3.1), regressed using the linear least squares. The final values are a = 0.46 and b = 0.93.*

Replacing the found values into Equation 3.1 and reorganizing it to express the calibrated magnitude equation for our test station site we obtain:

$$M_{TEST\_SITE} = 1.08 \times log_{10}(PGV_V) + 1.44 \times log_{10}(D) - 0.49 \tag{3.2}$$

To assess and to appreciate the magnitude calibration equation, we plot our magnitude estimates against the local magnitude as provided by the SED (Fig. 3.14): the largest difference is ca. 0.4 units, which is a reasonable value considering calibration using a single station. Although the magnitude equation was calibrated using data from $M_L$ 1.0 − 3.4 earthquakes, the fit to $M_L$ 3.5 − 4.2 events is very good. A final cross-check with SED's internal equation to link $M_L$ with observed ground motion and epicentral distance remains to be done.

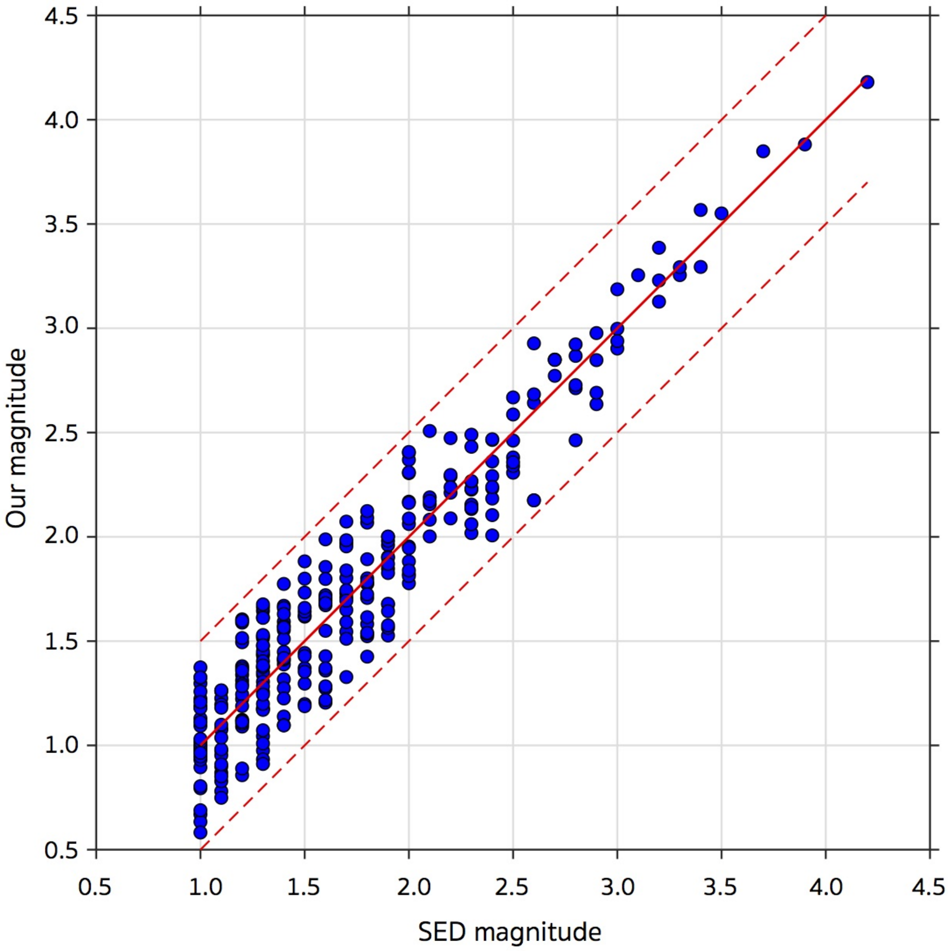


**Figure 3.14:** *Magnitude comparison plot. The SED-reported magnitude is plotted against our magnitude using the newly calibrated magnitude equation (Eq. 3.2).*

## 3.5 Why was the Raspberry Shake 1D selected?

Based on our tests and experience, we have selected the Raspberry Shake 1D seismometer for our educational seismology project in Nepal. It is an all-in-one, plug-and-play solution that integrates a good quality velocity sensor (geophone) and the digitizer in form of a Raspberry pi computer in a single box (Fig. 3.16). It is developed by the Seismic Observatory of Western Panama in Panama (OSOP[2], https://raspberryshake.org/) who provide fast reacting support. The cost of the sensor is somewhat higher than our initial expectation, but the ready internet connection and the good performance made us decide to revise our budget criteria and apply for funds to purchase sufficient number of instruments for Nepal.

[2]See here https://www.youtube.com/watch?v=6gWsJ2r2PJI

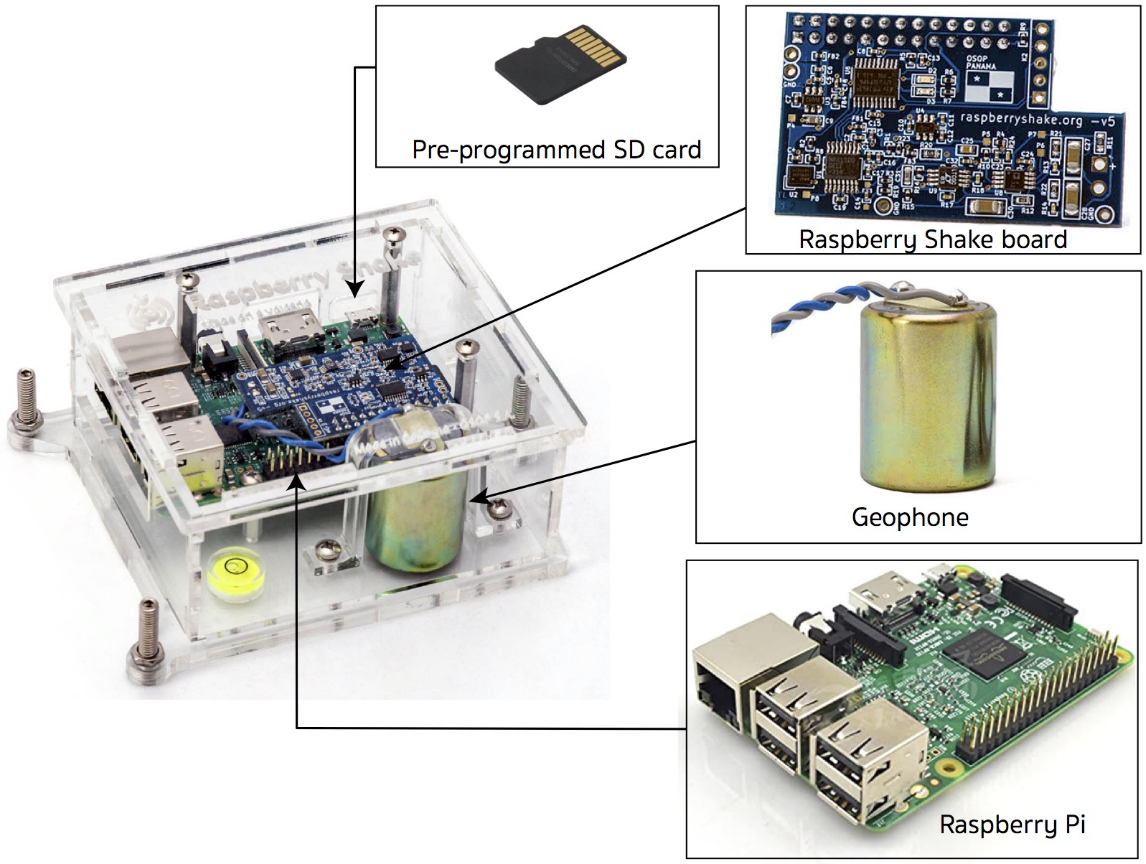


**Figure 3.15:** *Raspberry Shake 1-dimensional seismometer and components. Source: Raspberry Shake.*

### 3.5.1 Raspberry Shake 1D characteristics

**Sensor**

The sensors is a professional grade, commercial 4.5 Hz geophone with electronic extension to lower frequencies (< 1 Hz).

**Autonomy**

The RS1D sensor simply needs to be powered via Universal Serial Bus (USB). It doesn't need an operating system and can be functional already with an internet and power supply. A Wi-Fi solution is being developed.

**Sensitivity**

The sensitivity of the RS1D is claimed to be incomparably higher than other low-cost seismometers ($3.81 \times 10^8$ counts/meter/second with 10 % precision), and is very good also in our experience: it could record an earthquake of $M_L1.0$ at 36 km distance, and an

ML4.0 at 1'000 km distance, as well as large earthquakes worldwide. This is one of the greatest advantages over other low-cost sensors as it should be capable of recording several earthquakes per month in the seismically active region of Nepal. The 24-bit digitizer is used for the analog-to-digital signal conversion, and the latest release can record 100 samples per second.

**Frequency response, dynamic range**

The sensor's latest release is described to produce a flat velocity response in the 0.7 - 29 Hz frequency band. The ratio between the largest and the smallest signal that the sensor can record is called the dynamic range. Theoretical dynamic range of the RS1D digitiser is 144 dB where actual device reach 130 dB dynamic range at 1 Hz frequency. The peak-to-peak range of recording is 22 mm/s.

**Educational and low cost aspects**

A nice advantage of the sensor is that all of its components are visible, which makes it easy for demonstration. One can install it in a classroom for teaching purposes using the electric and internet connection. Real-time data can be displayed using EQInfo smartphone application (Weber and Herrnkind, 2014), or software such as jAmaSeis (Drago et al., 2009) and Swarm (by the USGS), among others. The price of a single component unit is less than 500 USD including licence.

**Connectivity and open data**

A major advantage is continuous data recording and near real-time data availability through the internet. The recorded data are directly stored on the central server, and become freely and openly available for everyone

**Standard data format**

The system saves data in the universally accepted miniseed format. A user can share data with seismic observatories worldwide in standard data streams (i.e. seedlink), meaning that these sensors have a real scientific value as they can complement classic seismological networks and become part of routine earthquake observations.

**Sustainability**

The Raspberry Shake system is fully compatible with current standards, so there is no more need for seismologists to maintain or develop specific softwares which is essential for the long-term sustainability of citizen observatory initiatives. Also, the producer uses a mix of open source and commercial software licenses for data sharing. The license is available at no additional cost for personal and educational purposes. All recorded data will be stored on the central server for 2 years free of costs. Currently, the manufacturer ensures that all data that the owner agrees to open will be made available without constraint on one of its servers. There is also a 1-year guarantee on each sensor.

**Easy-to-use, installation and maintenance**

A Raspberry Shake 1D is almost a plug-and-play sensor, and the configuration is straightforward. Installation can be done within a couple of minutes. It can run for a long time without any problem if there is stable internet and continuous power supply.

### 3.5.2 Examples of applications

The RS1D has been rapidly used to study different natural and environmental activities in many countries. Naturally, it has been found suitable for studying local and regional earthquakes (Anthony et al., 2019), but also to study rockfalls in the Swiss Alps (Manconi et al., 2018). In Taiwan, it is used to monitor debris flow in New Taipei city (Chu et al., 2019). Similarly, the sensor has been used to monitor seismicity in the Colima Volcano in Mexico[3], to monitor seismic and human activities in Strasbourg, France (Grunberg and Schlupp, 2019), to observe seismic activities in Washington D.C. area (Pulli, 2018), to educate citizens in Oklahoma (Walter et al., 2020), and to reduce seismic risk in Indonesia[4]. Interestingly, the Raspberry Shake 1D is proposed to use to develop a seismic network in Haiti for regional earthquake location and magnitude determination (Calais et al., 2019). Furthermore, along with advanced sensors, RS is used to study earthquake swarms close to hydrocarbon activities in the United Kingdom (Hicks et al., 2019). These positive experiences further convinced us about the choice of RS1D sensors for Nepal.

### 3.5.3 Raspberry Shake installation circuit

As a final preparation for installation in the field, the local field conditions were taken into account. In Nepal, having continuous power supply and stable internet connection are recent and great achievements, and these two connections are essential for a smooth station installation. At sites where national electric system is not installed, we relied on solar panels as alternate power supply. We mostly had access to wired internet connection, however Wi-Fi is also used in few sites in remote areas.

Every year more than 100 casualities by lightning have been reported in Nepal, with most of the fatalities in the pre-monsoon season. During lightning, electronic devices are damaged because of the flow of high current in the electricity system. To most optimally avoid such situations at our stations, as well as mains power (voltage and/or current) oscillations, we

[3]Mexico RS: https://raspberryshake.org/wp-content/uploads/2019/11/UGM-2019_compressed.pdf

[4]https://stirrd.org/2018/03/10/seismometer-in-schools-pilot-launched-in-central-sulawesi/

have included an uninterruptible power supply (UPS) in our station setup (Fig. 3.17). This provides some backup electrical power for a short period of time to the instruments in case of disruption, and longer duration outages of normal electrical service (load-shedding) are covered by an additional battery (Fig. 3.17). For real-time waveform display, most Nepali schools have a computer with Windows operating system available, and we could donate a few used computers to schools in need. We installed to appropriate software (e.g. jAmaSeis), and an increasing number of teachers and students started to use apps on their smartphones, also in communities away from the schools participating in our program.

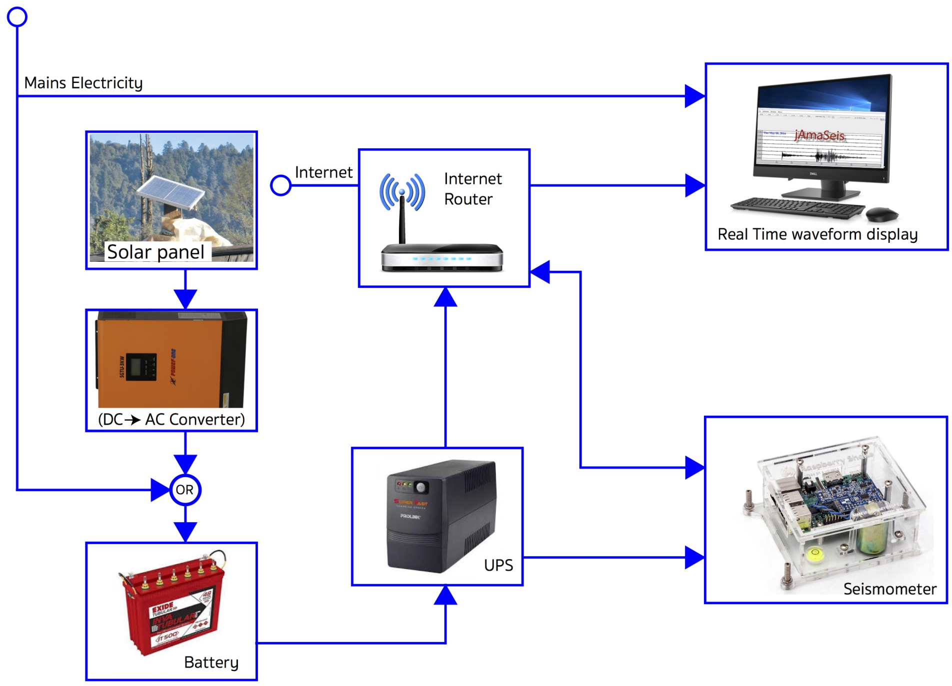


**Figure 3.16:** *Schematic diagram of seismometer station installation circuit for Nepali schools.*

### 3.5.4 Lockdown effect

At the end of 2019, a disease caused by a newly discovered coronavirus, COVID-19 has been spreading around the world, which also forced me to home-office work for writing up my PhD thesis. To contain the spreading of the virus, there are many efforts by governments, including banning or limiting people gathering, closing of schools and restaurants, and ultimately lockdown. In Nepal, the government had decided to go for nation-wide lockdown on 24 March 2020. As a result, the anthropic sources of seismic background noise have substantially decreased, and this effect became visible on our records.

Figure 3.15 shows the average ground displacement observed by some of our stations in Nepal (see network details in chapter 4), where curves in different colors are average daytime (7h-17h) displacement normalized to its respective maxima over a three-month time window.

The imposed lockdown has a strong impact on the observed displacement and its effect is prominent immediately after the announcement of isolation, with the amount of reduction varying as a function of station location between larger cities and remote areas.

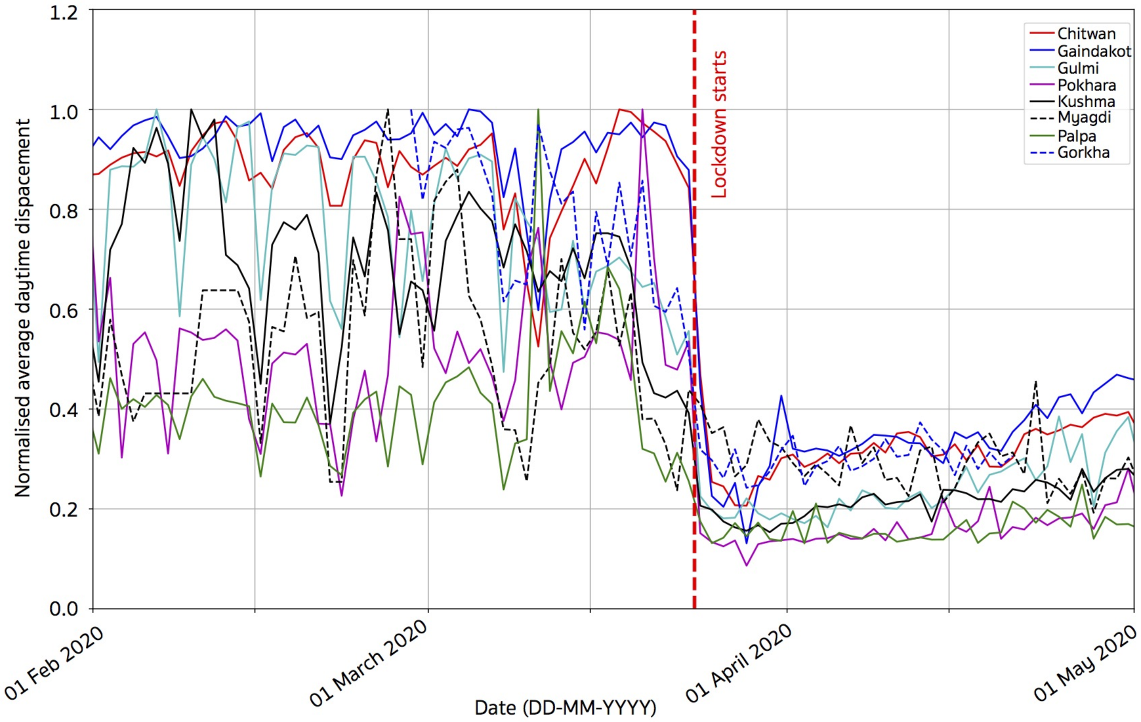


**Figure 3.17:** *Observation of ground displacement at stations in Nepal before and after the national-wide lockdown. The dashed red line refers the lockdown start date, March $24^{th}$ 2020, and the vertical axis is normalized average day-time ground displacement. Original signals are filtered in the 4 - 14 Hz frequency band.*

From these records we find that human activities have been really limited following the lockdown. In some roadside areas, for example Chitwan and Gaindakot, the ground vibration has reduced by a factor of three. This means that the majority of human activities have stopped in these areas: no students in the schools, no vehicles on the streets and highways, and machinery is not working near the stations. Even the nighttime noise is reduced (not shown), which may be due to closed industries and no traffic (only emergency work related vehicles).

The reduction on ground vibration is more important in big cities and related to traffic compared to the countryside. Such low levels of seismic noise were never detected since the seismometers were installed a year earlier, even in densely populated cities such as Pokhara. Furthermore, we observe that the seismic noise recorded during lockdown is equivalent to the lower limit of the noise level at the time of the main festive season in Nepal (equivalent to Christmas in western culture) in district headquarters, for example Gulmi, Kushma, Palpa and Gorkha. In the countryside, the lockdown cause reduction is relatively less, possibly as people must keep working on their own fields. Similar lockdown effects on Earth's background vibration are observed in Europe and around the world (e.g., Gibney, 2020), the details of which have been compiled by the seismology community in a large collaborative effort (including our work), resulting in an overview paper published in Science (Lecocq et al., 2020).

# Chapter 4

# Seismology at School in Nepal: a program for educational and citizen seismology through a low-cost seismic network


*This chapter is published as:*

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## 4.1 Abstract


Nepal, located above the convergent India-Eurasia plate boundary, has repeatedly experienced devastating earthquakes. During the 2015 magnitude 7.8 Gorkha earthquake, an often-reported experience was that people were not aware of the threatening seismic hazard and have insufficient level of preparedness. An important source of the problem is that earthquake-related topics are not part of the school curriculum. Earthquake education reaching a broad group of the population early in their lives is therefore strongly needed. We established an initiative in Nepal to introduce seismology in schools, with focus on education and citizen seismology. We have prepared educational materials adapted to the Nepali school system, which we distributed and also share on our program's website: www.seismoschoolnp.org. In selected schools, we also installed a low-cost seismometer to record seismicity and to allow learning-by-doing classroom activities. Our approach was very well received and we hope it will help making earthquake-safe communities across Nepal.

The seismic sensor which we installed in schools is a Raspberry Shake 1D (RS1D), this was selected based on its performance in laboratory tests and suitability for the field conditions. At a test site in Switzerland we were able to record magnitude 1.0 events up to 50 km distance with a RS1D. In Nepal, 22 such seismometers installed in schools create the Nepal School Seismology Network providing online data openly. The seismometer in each school

allows students to be informed of earthquakes, visualise the respective waveforms, and estimate distance and magnitude of the event. For significant local and regional events, we provide record sections and network instrumental intensity maps on our program's website. In 6 months of network operation, more than 194 local and teleseismic earthquakes of $M_L \geq 4$ have been recorded. From a local and a global catalogue, complemented with our own visual identifications, we have provided an earthquake wave detectability graph in distance and magnitude domain. Based on our observations, we have calibrated a new magnitude equation for Nepal, related to the epicentral distance $D[km]$ and to the observed peak vertical ground velocity $PGV_V[\mu\text{m/s}]$. The calibration is done to best fit local catalogue magnitudes, and yields the following equation: $M = 1.05 \times log_{10}(PGV_V) + 1.08 \times log_{10}(D) + 0.75$.

## 4.2 Introduction and background

Nepal is located above the Himalayan convergent plate boundary between the Indian and Eurasian plates (Aitchison et al., 2007), and consequently in the heart of the most active continental seismic hazard zone. The recent geological and geodetic shortening accommodated across the Himalayas is about 2 cm per year (Bilham et al., 1997; Lavé and Avouac, 2001; Jouanne et al., 2004; Zheng et al., 2017). The surface expression of this shortening is the Main Frontal Thrust, which continues at depth, to about 15 km below the surface, for more than 100 km towards the North, forming the Main Himalayan Thrust (Cattin and Avouac, 2000; Elliott et al., 2016; Duputel et al., 2016). This is the megathrust interface which hosts major earthquakes all along the 2'500 km long Himalayan range. The mountain belt has experienced devastating earthquakes throughout the geological, historical and recent past, claiming lives and causing significant damage. Nepal, in the central part of the Himalaya, occupies nearly one third of the mountain belt, and is the home of ca. 30 million people who live in a very high seismic hazard zone.

The largest instrumentally recorded earthquake in Nepal, the 1934 Mw8.2 event has been followed by the Mw7.8 Gorkha earthquake and a second, Mw7.3 event in 2015 in Central Nepal (Figure 4.1). Paleoseismic investigations along strike of the active frontal thrust reveal further large historical earthquakes (e.g., Bollinger et al., 2016), the oldest known earthquake described in a primary source having occurred in 1223 (e.g., Bollinger et al., 2016), but its description remains unreadable due to defaced letters and words. The greatest event in Nepal, which is also the most recent great earthquake in Western Nepal, occurred in 1505, as reported in historical chronicles (Ambraseys and Jackson, 2003; Ghazoui et al., 2019). The elapsed time since then leads to the existence of a well-identified seismic gap in which another large earthquake is due (e.g., Bollinger et al., 2016). This fits the overall view of the seismic cycle in the Himalayas, which has recorded a major earthquake all along the mountain belt in the past 500 years (Hetényi et al., 2016b). Earthquakes are the most common and most deadly natural disaster in Nepal, claiming more than 19 thousand lives since 1934, which is

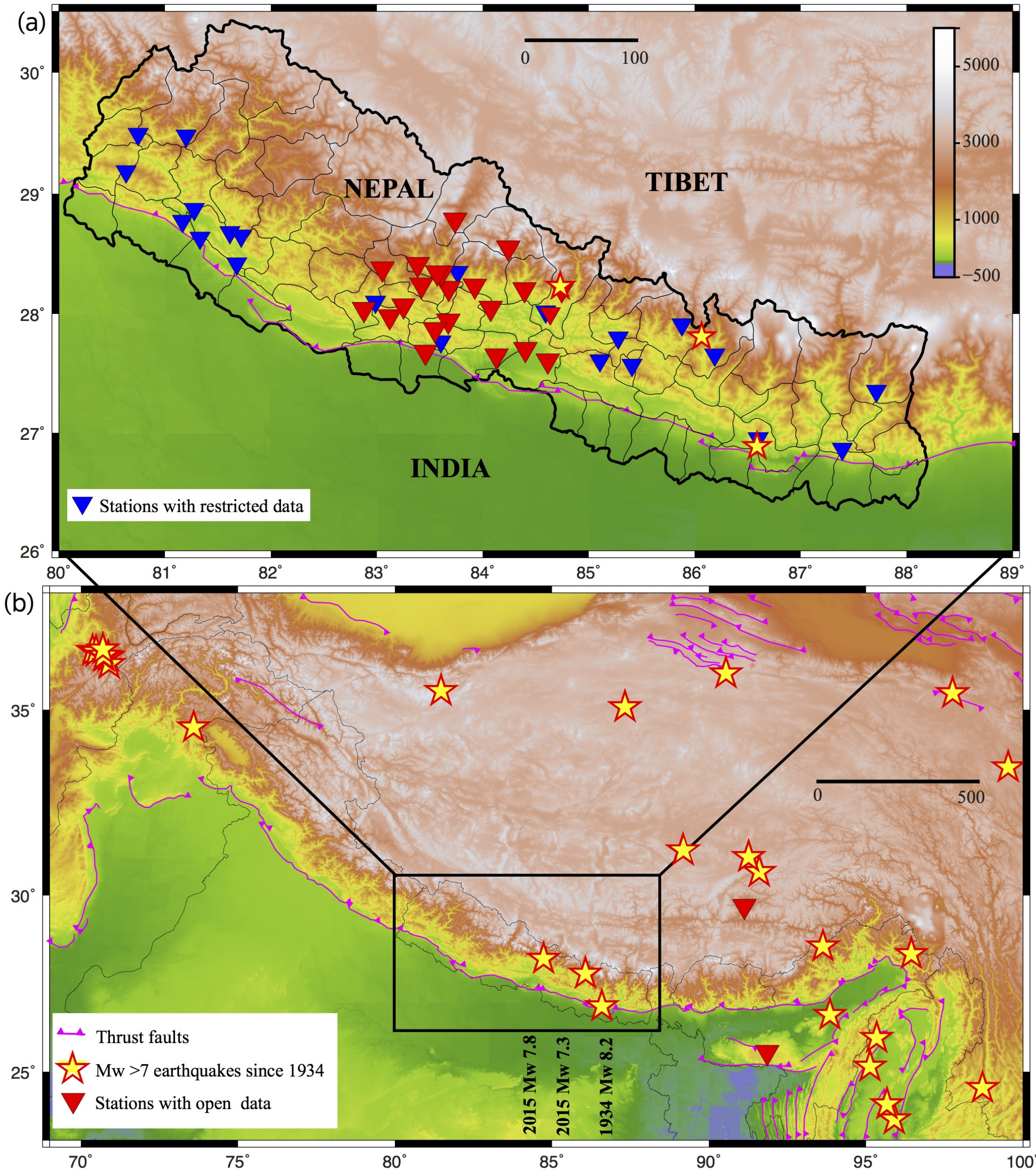


**Figure 4.1:** *Studied area maps. (b) The Himalaya-Tibet region, with large and great earthquakes ($M \geq 7$) since 1934 from the USGS catalog. Permanent seismic stations with open data are shown in red. (a) Focus on Nepal, showing 21 permanent seismic stations of the National Seismological Center with restricted data in blue, and 22 Nepal School Seismology Network (this project) stations in Western Nepal with open data in red. Pink lines are thrust faults in the area (Styron et al., 2010). Distance scales are in kilometers.*

more than 80 % of the total casualties from natural disasters (MoHA, 2015).

Despite the clearly high seismic hazard, permanent seismological observatories with open data are rare in the region (Fig. 4.1). The only government facility in Nepal is the National Seismological Center (NSC), which has been operating a permanent seismic network for decades within the framework of international collaboration, and is currently operating 40 short-period and broadband stations in the country. The NSC publishes earthquake information to the population for earthquakes inside Nepal when the local magnitude $M_L$ equals or exceeds 4. Other seismic networks in the area are typically temporary research networks, they are installed for a few years, but their data is only openly accessible after a few years of delay and in a format far less comprehensible to the general public.
Scientific results based on these seismological data are abundant and should be acknowledged for pushing the limits of knowledge in an area where fieldwork conditions are not straightforward. Geophysically imaging the structure of the orogen at depth (e.g., Schulte-Pelkum et al., 2005; Nábělek et al., 2009; Singer et al., 2017; Subedi et al., 2018) is very important to establish quantitative models of seismic hazard. Locating the seismicity both during the inter- and the post-seismic periods (e.g., Bollinger et al., 2007; Adhikari et al., 2015; Diehl et al., 2017; Hoste-Colomer et al., 2018) are equally important to understand the mechanical behavior and dynamics of the orogenic wedge. Nevertheless, state-of-the-art geoscience knowledge reaches only a very small fraction of the population. For example, recent publications report that there is an increased risk of a future major (M>8) earthquake in the area between west of Nepal and India (Galetzka et al., 2015; Avouac et al., 2015), and recent estimates of average return period for great earthquakes ranges from 300 to 870 years plus uncertainties (Avouac et al., 2001; Bollinger et al., 2014). However, the local population has almost no information about these recent findings.

What the local population is aware of are their own felt-earthquake experiences, the fresh memory of the 2015 Gorkha earthquakes, and the announcements of the NSC ($M_L \geq 4$ events in Nepal). The latter information is spread through the NSC webpage, through social media, and – with some time lag – through newspapers and online articles. Still, the general level of information about what a person should do in case of a seismic event is surprisingly low. Citizen's awareness is a key element for seismic risk mitigation, which is clearly missing in the field. Some efforts by various organizations after the 2015 Gorkha earthquake around the capital city Kathmandu were initiated, but these have not reached people in the countryside. The majority of Nepal's population has either a mythological perception or no clear idea about what causes earthquakes and what is the best behavior and practice to protect themselves. In addition, ways to communicate about earthquakes and related topics are not well established in the community.

Our initiative aims to tackle two challenges with a combined approach, for which we start our program in an area of high seismic hazard but relatively limited (although not the lowest) level of information in the country. First, it is crucial to increase the awareness of the local population about the fact that they live in a region where the accumulated energy is sufficient to produce a large earthquake. Second, we need to teach and train citizens in the community for better preparedness and what actions they can undertake to lower their chances of being hurt. In the countryside, no other source of information like television and newspapers are easily accessible, and also in cities it is difficult to gather knowledge from these kinds of sources. Hence, we found that the best way to engage people in learning about earthquakes is through the educational system, as what information students receive at school can be transmitted to their families and communities most efficiently.

In order to undertake this approach, it is necessary to connect communities to citizen science in Nepal. That is why we installed the first 22 low-cost seismic stations in local schools as a part of the Nepal School Seismological Network (Fig. 4.1). This network is already used both for teaching and for sharing locally recorded data openly. We hope that the example set in Western Nepal will spread across the entire country, and that our program helps to make earthquake-safer communities.

## 4.3 Preparatory phase

The project's preparatory phase included planning, laboratory, logistic and field work, which we carried out as mostly parallel tasks as follows: (1) definition of the study area and site planning, (2) preparation of educational material, (3) seismic sensor survey, testing and selection. This section describes our approach in detail, and the next section focuses on the implementation in Nepal.

### 4.3.1 Site selection

Within the broader frame of educational activities, we planned to build the Nepal School Seismic Network (NSSN) in western Nepal (83 - 85°E) over an area of ca. 200 km east-west extent, including the epicenter village of the 2015 Gorkha earthquake and westwards from there. The area is relatively densely populated, but is too far from the capital Kathmandu to be included in initiatives aiming to implement earthquake education. There were some case studies for earthquake risk management and risk mitigation in the Kathmandu valley (JICA, 2002). However, even after the 2015 Gorkha earthquake, when national and international non-governmental organizations had tried to initiate earthquake preparedness projects around Kathmandu for local people, the efforts remained geographically limited (see e.g. the following reports and websites on disaster management and safer constructions: USAID, www.safernepal.net, Rosie-may; other projects are on the way). Our approach, located away from the capital, is different, and complementary in scope.

To the best of our knowledge, no efforts have been reported outside the Kathmandu valley for educational and citizen seismology. We have selected Western Nepal to start our program because (i) people have very limited to no opportunity to learn about earthquakes, (ii) there was no major earthquake in the last 500 years and therefore the probability of such an event is high, and (iii) travel time between the different sites is within reasonable bounds. The main goal in setting up the NSSN was therefore to establish a broadly and possibly homogeneously distributed network across the region, to initiate earthquake education in schools and also to build a seismic network able to provide useful data for both education and basic research. To establish a broad base for site selection, we used social media (Facebook and twitter, both popular in Nepal) to spread information about our program, and also asked interested schools to fill out a request form. An excellent knowledge of the region's geography and social relations, as well as communications skills were required for this step. The non-Nepali co-authors of this work believe that foreigners alone would have had no chance to start and implement this project due to a lack of sufficient local contacts and knowledge of Nepali society. More than 100 schools submitted a request form from the defined study area. Out of these, we selected 22 along the criteria for good sites as follows:

- the school hosts a large number of students from the area,
- high motivation of the school administrative board,
- feasibility to install the seismometer on the ground floor,
- school located relatively far from a major road, village, or city, to avoid cultural noise (minimum distance from a road or highway must be 200 m),
- the school having its own internet connection and alternate power supply (technical priority criteria),
- the school is reachable by vehicle or short walk.

Each submitted form was evaluated individually to see which site met as many criteria as possible. In many cases, compromises were necessary. We also aimed to have an overall geographical distribution of schools that covers the study area evenly. With the final selection of sites, we covered the administrative regions of Province 5 and Gandaki Province in western Nepal. Finally, to prepare the field implementation phase, we have validated our remote site choices by visiting all schools in person during a reconnaissance trip in April-May 2018. The selected school's name is listed in Supplementary information[1], the map of the NSSN is shown in Figure 4.1, and photos of two typical school buildings are shown in Figure 4.2.

### 4.3.2 Educational materials

School education in Nepal occurs at basic and secondary level (Table 4.1). Schooling begins with basic level and the school starting age for children is five years old; however, attendance

[1]See Table 1 in supporting information file at https://www.frontiersin.org/articles/10.3389/feart.2020.00073/full


**Figure 4.2:** *School buildings participating in our program. (a) Shree Himalaya Secondary School in Barpak, Gorkha district. A reinforced cement concrete (RCC) building was newly constructed after the 2015 Gorkha earthquake. A total of 672 students study in the school. (b) Shree Bhanubhakta Acharya Secondary School in Galyang, Syangja district. RCC building, but the third story is not cemented: it is brick, with tin roof on top. A total of 925 students study in this school.*

is not compulsory. As of the 2017 Department of Education survey, a total of 35'222 operational schools (from grade 1) received a total of 7'752'601 pupils (MoE, 2017), which is more than 25 % of Nepal's population. We therefore believe that the schools are the best platforms to share the required knowledge with the community, as relevant education not only teaches the children, but, through their families also reaches further into society. Seismology is not part of the curriculum in schools, a problem we aim to tackle in our program towards better preparedness.

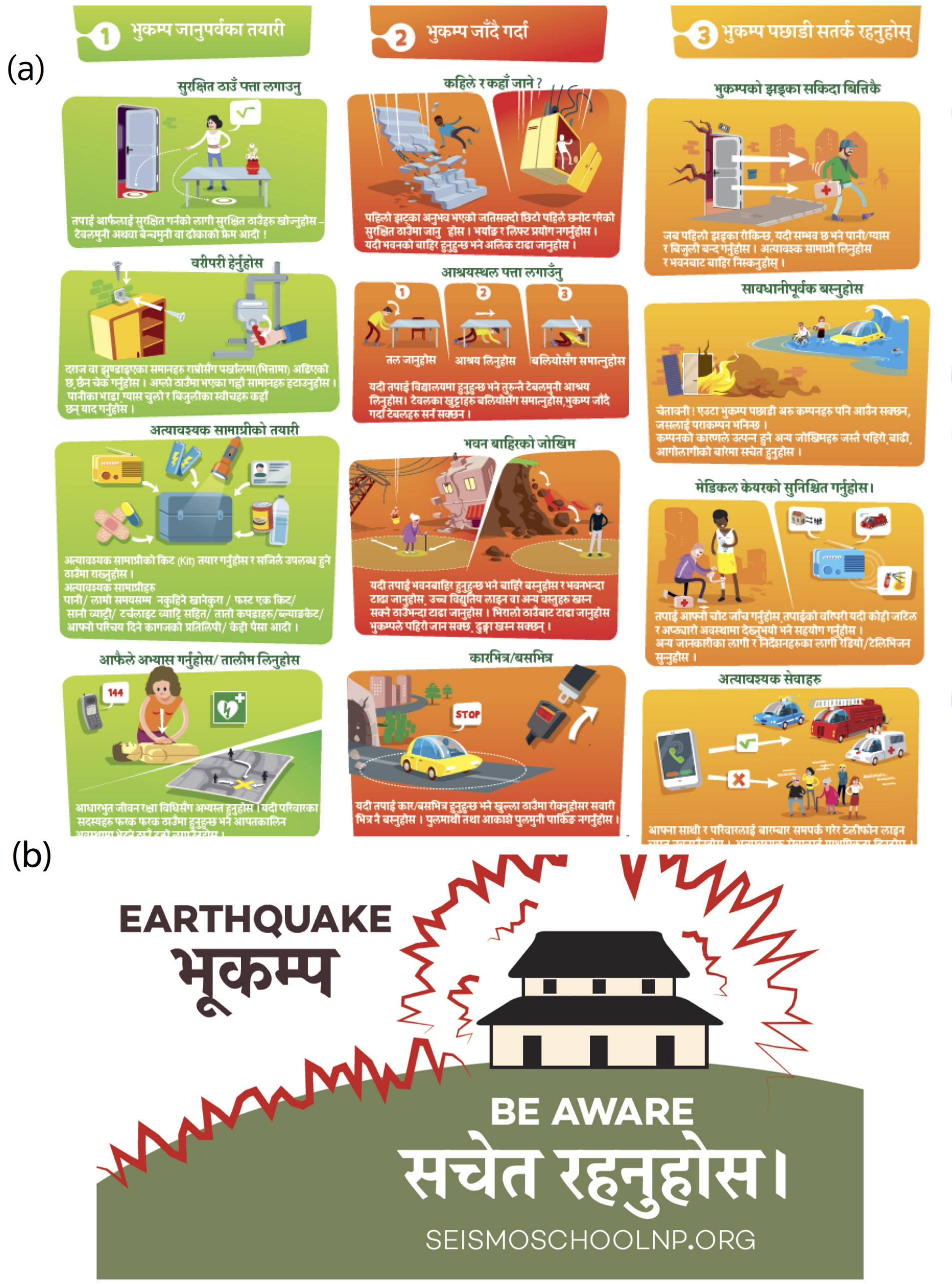


**Figure 4.3:** *(a) An important teaching material: a flyer prepared in Nepali language on what to do before, during and after an earthquake, illustrated in detail with pictures. The flyer is adopted from the English version which was initially prepared by and for the Earthquake Education Center, Switzerland. The full flyer is freely available from our website directly at :http://seismoschoolnp.org/wp-content/uploads/2019/11/Be-Prepared-Nepali.pdf. (b) Earthquake awareness sticker aimed as a reminder, in English and Nepalese language.*

In the context of Earth science education in Nepal, we could find only very limited information about earthquakes in textbooks. We therefore based our approach on existing educational seismology projects around the world. There are a number of similar initiatives running

| **Education level** | **Grade** | **Student's age** | **No. of schools** | **Students** |
|---|---|---|---|---|
| Early childhood | | $< 5$ | 36'568 | 958'127 |
| Basic | 1 – 5 | 5 – 9 | 35'211 | 3'970'016 |
| | 6 – 8 | 10 – 12 | 15'632 | 1'866'716 |
| Secondary | 9 – 10 | 13 – 14 | 9'447 | 970'720 |
| | 11 – 12 | 15 – 16 | 3'781 | 584'072 |
| University campuses | Bachelor & above | $> 16$ | 15(1'407) | 361'077 |
| **Total** | | | | **8'710'728** |

**Table 4.1:** *Education system in Nepal and key numbers, according to Department of Education (MoE, 2017).*

currently (or until recently), mostly in developed countries, such as the UK school seismology project, the Swiss *Seismo@school* project, the Irish Seismology in Schools project, the Texas Educational Seismic Project (USA), and the Australian Seismometers in Schools project. We have held discussions with specialists from different countries to gain knowledge from their experiences and to build up ideas for the educational material development for Nepal. We also looked for existing materials which might be suitable for our purpose and context. Numerous suggestions and experiences shared by experts were taken into account in the preparation of several educational materials adapted to the Nepali school system and language.

One of the most important educational material is a flyer, as partially shown in Figure 4.3a. This leaflet was designed by the Earthquake Education Center in Sion, Switzerland and translated into Nepalese for our schools. This leaflet delivers detailed information on how to prepare before an earthquake, how to save one's life during an earthquake, and what to do after an earthquake, well-illustrated with drawings and sketches. Information about the contact person and/or office in case of an earthquake, and games related to earthquakes for kids are also included in the flyer. Further educational tools were prepared in advance of our field visit, which we describe in detail under the implementation phase of the project in section 3.1.

### 4.3.3 Instrument selection

The seismic sensor should achieve two different goals of the program, namely to be able to detect relatively low magnitude earthquakes, and to be able to be used as a teaching instrument to share knowledge with students in an efficient way in the classroom. Therefore, we needed to find a compromise between a simple pendulum which is a common instrument in Nepali schools to teach physics, and research quality modern broadband sensors that are very expensive. Following literature review and based on personal communications with several experts in the field, we found many low−cost seismological instruments which seems to satisfy both our target criteria. We carried out a market survey on low-cost sensors available around the world by defining criteria as follows:

- total cost including the delivery charge is cheap, below 500 USD,
- easily applicable for educational purposes,
- reasonably high sensitivity to detect local earthquakes,
- easy to handle,
- possibility to record data without an additional computer.

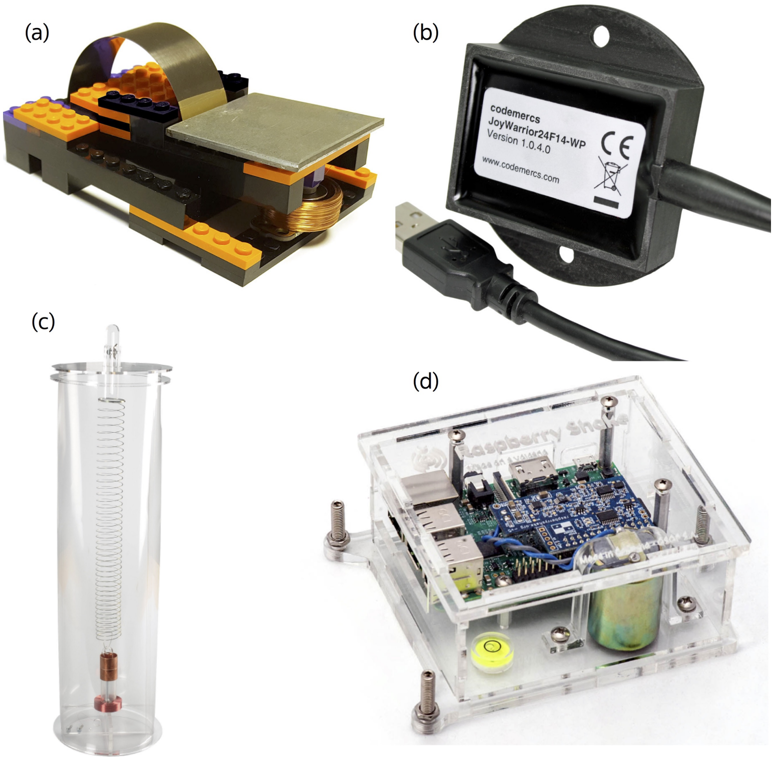


**Figure 4.4:** *Low-cost sensors purchased and tested before selecting one for our program: (a) Lego, (b) Quake Catcher, (c) Slinky, (d) Raspberry Shake 1D. See Table 4.2 for the characteristics of each sensor and our evaluation.*

| | **QCN** | **LEGO** | **Slinky** | **AS−1** | **SEP** | **RS1D** |
|---|---|---|---|---|---|---|
| Sensor | Digital accelerometer | Analog | Analog | Analog | Analog | Digital geophone |
| Components | 3(X-Y-Z) | 1-vertical | 1-vertical | 1-horizontal | 1-horizontal | 1-vertical |
| Sensitivity | Low | High | High | Low | High | Very High |
| Bandwidth | 10 s - 20 Hz | 2 - 20 Hz | 1 - 20 Hz | 2 s - 3 Hz | 20 s - 10 Hz | 1.25 s - 29 Hz |
| Digitizer | 16 bit | 16 bit | 16 bit | 12 bit | 16 bit | 24 bit |
| Timing | PC clock | PC clock | PC clock | PC clock | PC clock | Network Timing Protocol |
| Continuous data available | No | Yes | Yes | Yes | Yes | Yes |
| PC needed | No | No | No | No | No | Yes |
| Real-Time data | Yes | Yes | Yes | Yes | Yes | Yes |
| Additional software needed | Yes | Yes | Yes | Yes | Yes | No |
| Installation procedure | Simple | Difficult | Difficult | Difficult | Difficult | Simple |
| Overall user experience | Complex | Simple | Simple | Simple | Simple | Plug-and-play |
| Educational appeal | Poor | Good | Good | Good | Good | Medium |
| Manufacturer | Stanford University, United States* | Mindsets, United Kingdom | Mindsets, United Kingdom | United States seismology community | United States seismology community* | OSOP, Panama |
| Approximate cost (USD) | 77 | 210 | 137 | 500 | 700 | 375 |

**Table 4.2:** *List of seismological instruments tested for the educational purposes and comparison of their characteristics. A small part of the information (on AS-1 and SEP) is from Zollo et al. (2014). *sensor no longer manufactured.*

Our initial list included a total of 16 types of seismometers, some of these were already adopted in programs with similar purposes to ours (e.g., in the UK, at IRIS). From this list and using the criteria above, we have selected 4 types of sensors: the Quake Catcher Network (QCN), the Lego, the Slinky, and the Raspberry Shake 1D (Fig. 4.4). We purchased a sample instrument of each, and carried out various tests in laboratory conditions to assess their respective sensitivity, detection threshold, noise level, frequency band, ease of use, adequacy to field conditions, etc. Our findings are synthesized in Table 4.2, in which two other sensors are also included from Zollo et al. (2014). After this comparison of performance, the RS1D instrument was found best for our purposes and selected for our project. Subsequently, we found that Anthony et al. (2019) judged the RS1D suitable for studying local and regional earthquakes.
To complement our laboratory tests, we also installed an RS1D sensor at a field test site at a low-noise location in Grimisuat, in Valais canton, Switzerland. This region is known to be that with the highest seismic activity in Switzerland, with recurrent damaging events. The latest major event occurred in 1946 in Sierre, and had a magnitude of 5.8 with strong aftershocks (Fäh et al., 2011). We installed a sensor in March 2019, and shortly after we were able to detect an earthquake of $M_L 1.0$ at 36 $km$ distance, located by the Swiss Seismological Service (SED). This was a surprise to us, and the good performance of the sensor was confirmed by the recording of a *"footquake"* at less than 3 km distance following the hitherto earliest goal (10 seconds after kick - off) scored in the Swiss top league which was celebrated by ca. 7'000. At our test site, during 6 months of operation, more than 210 events ($0.4 \leq M_L \leq 4.2$) have been recorded. These events are extracted from the SED web catalog, also available through arclink. The observed peak ground velocity values are discussed below. The data recorded at this station is available as sensor ID R291C of the AM (RaspberryShake) network, and real-time data can be viewed directly at $https://raspberryshake.net/stationview/\#?net=AM\&sta=R291C$.

## 4.4 Implementation in Nepal

After several preparatory discussions, we decided to apply a people-centred approach in our project, where students and local people have the opportunity to directly interact with scientists; this is considered to be more effective than a top-down approach (Scolobig et al., 2015). The preparatory phase of fieldwork consisted of a ca. 1 - month reconnaissance trip in Nepal during which all selected schools were visited and cooperation agreements signed, as well as the first earthquake-focused classes were taught (Spring 2018). The implementation phase started with a 2-day educational workshop for school teachers in Pokhara, followed by visits to every school where the low-cost seismometers were installed and full educational activities started (Spring 2019). The implementation phase lasted 34 working days including all travel to Nepal and ca. 3'700 km travel on roads in Nepal in ca. 480 hours. About 6 months later, all sites were visited again for station maintenance (where needed) and updates on the educational side. Up to now, a total of ca. 77 extended working days (ca. 980 hours) and ca. 9'200 km distance travelled were spent in the field.

### 4.4.1 Educational implementation

During our early visits, we could ascertain that schools play a vital role in teaching the essential elements of common values and culture. The teachers were well respected, the students still wear uniforms (sometimes classical, sometimes modern), and in most cases a class or group of students were waiting for our visit. Therefore, teaching earthquake related themes to students in schools still seemed a good idea after the field visit. A critical element was to do most of the work in the Nepali language: while most teachers we met spoke English and most students understood English, it was easier for them to talk in Nepali and ask practical questions, or simply to overcome a normal level of shyness.

During the reconnaissance trip, we talked to the school principals and management committees about our program and its benefit to the community. The level of interest was very high and they were excited to see the appearance of someone for earthquake education in the school for the first time ever. We have given a few lectures and taught students key information about earthquakes in every school. In our experience, students are highly interested to learn about earthquake science, but they lack relatively basic knowledge to start with. We have focused on delivering some of this knowledge in an easy and simple way. For example, regarding the Himalayas, we talked about the height of Mount Everest, which was known to every student, but also the age of the Himalayas, to which nobody knew the answer (despite some geological evidence sold in the area as tourist souvenirs). Giving the age ourselves, we could then continue onto the formation of the Himalayas as a consequence of subduction of the Indian plate beneath Tibet and the collision history. This then led onto moving plates, which are the source of energy stored beneath the surface, episodically released to create earthquakes. We also demonstrated what can be done in case an earthquake hits the school or their homes, and performed earthquake drill exercises to shelter beneath tables, doorframes, or to evacuate to a safe place.

A delicate point of the communication was not to cause confrontation between science and people's religious or mythological views. We prepared this partly with the help of a Hinduism specialist. The strategy for teaching and discussions relied on two main points. First, to express that we have come to explain our views, and not to argue with their devout opinion or judge in any way. Second, we presented them a picture of the Earth, showing symbols of twelve major religions that exist, and then added symbols representing research and science, which is another view on how the Earth functions, the one which we came to present them. This strategy has worked well so far.

During the reconnaissance trip, we had already distributed the Nepali earthquake preparedness flyers (Fig. 4.3a). We added further elements to this in our main fieldwork in 2019. We designed a 9-by-5 cm sticker (Fig. 4.3b) to remind people about earthquake hazard, which we distributed to students and teachers (3'000 copies, >100 for each school so far), which should increase people's level of awareness. We also prepared an "Emergency Meeting Point" sign in Nepali, of which we distributed plasticized copies to each school. All these materials are freely available for download from our program's website Download page. Moreover, we have offered a slinky to each school: a colorful plastic spring with the help of which teachers can demonstrate P and S wave propagation in the classroom (Fig. 4.5).


**Figure 4.5:** *Educational demonstration examples. (a) Nature of the S-wave propagation using a slinky, explained by Dr. Paul Denton (with microphone) and performed by a voluntary participant during the First International Workshop on Education Seismology in April 2019 in Pokhara, Nepal. More than 80 school teachers participated in the workshop. (Photo Credit: Peter Loader). (b) Shiba Subedi (in T-shirt) demonstrates a P-wave using a slinky and discusses its nature with students in Balmandir Secondary School, Gorkha district. (Photo Credit: School). All people or their legal representatives on the photos have agreed to be taken on picture and to be presented in frame of this research project.*

### 4.4.2 Workshop

Even though our occasional visits to the schools with lectures, training and discussion are a special opportunity for both students and teachers, this effort alone would not be sufficient to reach our goals, either in terms of education of the topic, or to reach further into their communities. To increase the frequency and efficiency of learning, we therefore organized a workshop primarily for school teachers at the beginning of the implementation phase, and in the center of the study area, Pokhara. This event was very important both for knowledge transfer and for crossing the language boundaries: international experts presented their knowledge in English to 96 local participants, who then are able to disseminate this in the Nepali language to their respective audiences. The 2-days of workshop allowed plenty of time for discussions, translations, and also for sharing educational experiences between

Nepali and foreign school teachers. Out of 96 participants, over 70 were teachers from the 22 selected schools and further 10 from other, interested schools (mainly science, computer science, social subject teachers, as well as school principals), and there was a representative presence of the Province, of the Nepal Army, Nepal Police and Nepal Armed Police Forces, of the National Seismological Center, a few university and college students, as well as several journalists. The teaching by the international experts covered a broad spectrum of topics, from wave physics to Himalayan geology, earthquakes to plate tectonics, teaching methods to practical advices regarding earthquake preparedness, and several demonstrations with and without seismometer involving highly motivated volunteers from the audience (Fig. 4.5). A local earthquake occurring during a workshop session provided a very good demonstration and analysis topic. All the workshop material, including videos, is freely available from our program's website. Furthermore, a number of relevant and presented Earth Learning Ideas (www.earthlearningidea.com) are also directly linked.

One of the most interesting session of the workshop was the very wide ask-me-anything session. The presenting experts received a plethora of questions from the audience, some to clarify terms and concepts, but some of them really unexpected which lead to very interesting discussions. Here we list a few examples:

- Do tectonic plates always move in the same direction?
- Do you necessarily make earthquakes on faults?
- Why do mythological explanations of earthquakes often involve animals?
- Which discipline studies the relationship between Hinduism and earthquakes?
- f the Earth is an ellipsoid, with the poles being closer to the center of Earth than the equator, is the heat flow higher at the poles?

The full board of experts answered all questions based on their scientific, technical and personal knowledge, sometimes helped by Nepali translations. The event was a big success according to both the participants and speakers, and the teachers seemed to leave happy and with a high level of satisfaction. The school teachers reported that the workshop greatly helped them to make their first steps of teaching earthquake related topics in the classroom, and that the workshop format was helpful for an easier transfer of new knowledge. They were grateful for the memorable event, and that the organizers cared more about their earthquake safety than they themselves. The presence of many journalists from different media had a high impact regarding earthquake awareness, as the workshop and the program featured in 23 articles in national and regional newspapers, and in an extended live interview on the most widely watched Nepali television station. This ultimately increases the attention of people towards earthquakes and education of related themes. Based on the overall experience, we believe that this workshop made a long-term impact and contributed to earthquake-safer communities in Nepal.

### 4.4.3 Seismological implementation

The visit of the schools started immediately after the workshop, and by early May 2019 we had successfully installed the Nepal School Seismology Network (Fig. 4.1). The preparation for the full network installation in the field was based on the useful experience and lessons learned from the pilot station. By the end of the field work, all 22 RS1D seismometers had been installed on the ground floor, in most cases in the computer lab, the principal's room, or the science lab. We fixed the sensors on a small wooden platform cemented to the ground to avoid minor flooding. In the future, we plan to replace the wooden platform by paving stone or small cement platform. We also added either a simple (wooden box) or thermal (survival sheet covered polystyrene box) shielding around the sensor. Each station is also equipped with an uninterruptable power supply, and wired internet connection directly from a router. The NSSN can be cited through this article as well as under the digital object identifier 10.5281/zenodo.3406345. Raw seismological data from the NSSN is available through RaspberryShake, currently archived for 2 years, and NSSN stations are also regrouped under the virtual network virtual network. The data recorded by the NSSN can be downloaded freely via the fdsnws server with RASPISHAKE network name for wanted stations.

To facilitate educational activities and also troubleshooting simple problems, we prepared detailed guidelines on how to visualize waveforms recorded by the seismometer on a computer, how to use the EQInfo smartphone application (Weber and Herrnkind, 2014), and how to estimate magnitude and distance of local earthquakes from their own school's waveform recording. This document was distributed in every school and is also published at our website. We encouraged teachers to spread the information to citizens from the community, so that they can also share the experience without being at the school. Teachers report they use the *EQInfo* application for classroom activities.

A few participating schools have had the opportunity to receive additional funding from the local government to facilitate the logistics necessary to host an NSSN station. For example, Prabha Secondary School, Pyuthan has been selected by the Information and Communication Technology program and awarded ca. 5'000 USD from the Nepal government to equip a full computer room, purchase an alternate power supply, and to establish the internet connection for the school. Janak Secondary School, Gaindakot has received ca. 1'200 USD for creating a new, wired internet connection and power backup installation from the nearby Gaindakot Municipality, Nawalpur district. In the majority of schools, the seismometer is installed in a room corner separated by a thin wooden or aluminum wall, which improves signal-to-noise ratio, visibility and security (Fig. 4.6). We are proud to report that we also reached the epicenter village of the 2015 Gorkha earthquake, Barpak, a remote place where 72 people died from the most recent major earthquake. At the moment of our first field visit, people were back to daily business after the devastating earthquake, but schools were in temporary shelters. By the time of the installation, the school managed


**Figure 4.6:** *Example of the setting of an installed seismometer, in Shree Siddha Baba Secondary School, Gulmi district. The sensor is installed on the ground floor by making a partition in the Accounting Room; it is fixed to a wooden block which is itself fixed into a ca. 2 cm thick cemented base on the ground (inset). The station is connected to a desktop computer for real-time data visualization via the jAmaSeis (Drago et al., 2009) software. Detailed information on how to visualize waveforms on a smartphone using the EQInfo app is printed on the wall (A4 paper). The word "Seismometer" is written in on the wall in Nepali (and English) language.*

to receive support from the government-owned telecommunication service provider, Nepal Telecom (https://www.ntc.net.np/), to install the first wired internet connection in Barpak, which made the installation of the seismometer possible.

During the sensor installation, schools have invited high level authorities from the district (e.g., Mayor of the municipality, Chief District Officer, etc.) to show how the sensor records earthquakes, and to demonstrate that the school participates in the earthquake education program. The local news coverage about seismometer installation typically followed within hours or one day (see at media mention page). Since the entire network has been installed, we are communicating with schools using social media (twitter, Facebook) to keep the teachers' attention on the project. On our program website, we are posting figures of recorded waveforms from local, NSC-reported earthquakes. Our approach has been very well received by schools and also appreciated by the local governments. We hope that the ideas will spread to other regions of the country as well, and we will seek opportunities in this direction.

## 4.5 Results and discussion

### 4.5.1 Education

Teachers are at the first line of communication with the students. With high motivation, they are doing regular exercises with their students by showing waveforms recorded by the seismometer at the school (mostly for $M_L \geq 4$ local earthquakes). In each school, we encouraged teachers to practice evacuation exercises. The lessons learned from these drills helps the school community to respond more efficiently in case of a large earthquake, which increases the school's resilience. Teachers gave very good feedback on the main workshop and took it as a great opportunity to learn about earthquakes at their level. *"I am more interested in Earth sciences after this workshop"* said one teacher after the conference; a school principal expressed his gratitude because we were more worried about their earthquake safety than they were.

To evaluate the efficiency of our program and to assess the level of knowledge before its start and after one year of operation, we conducted a survey during the reconnaissance trip. A representative group of students from the selected schools, teachers and local people completed the survey with ca. 30 questions, and ca. 350 full sets of answers were collected. We plan to carry out the second survey in 2020 and compare it to the first one's results to analyze the changes our program may have promoted.

With our program, school teachers estimate to have reached a broad audience in the studied area: directly more than 18'000 students benefited from the program, and indirectly ca. 150'000 people in the region could have been reached (Supplementary Table 1[1]). While evaluating the indirect effect, an average family size in the community and the sociological situation were also taken into account. To share our activities and knowledge continuously with an even broader community in Nepal, we have developed the program's own web-page (www.seismoschoolnp.org). All materials for the education, information of recorded earthquakes, guidelines for exercises, important questions and answers are available on the webpage. This page had 14'689 visitors in 15 months (last access on 21 May, 2020).

### 4.5.2 Seismology: waveforms and instrumental intensity map

The NSSN was successfully installed by May 2019 and operates well since then. While 18 stations have been recording data continuously, four others encountered problems due to the unstable internet connection and/or power supply, therefore a small amount of data is missing from those sites. In the monsoon season, (only) one of the sensors broke, which we could then replace. The site selection criteria, as described earlier, made us make compromises between education and seismological purposes. For example, a station in a populated area will reach more people through education, but the site will have a higher noise level. Using the data from June to December 2019, hourly power spectral density probability density functions (PSD PDFs) have been computed, with 50 % overlap. Looking at the median values of these by station (Fig. 4.7), most of sites are below the high-noise model (Peterson, 1993), whereas 3 sites Chitwan (R8C46), Gaindakot (R6EC4) and Nawalparasi (R51F6) are badly affected by daytime noise (road traffic, urban environment) but are still able to provide useful data at night. Nevertheless, most stations seem to represent a reasonable compromise between education and observation, and some have even very good signal-to-noise ratios. We have observed that the low-cost seismometers record earthquakes not only from local

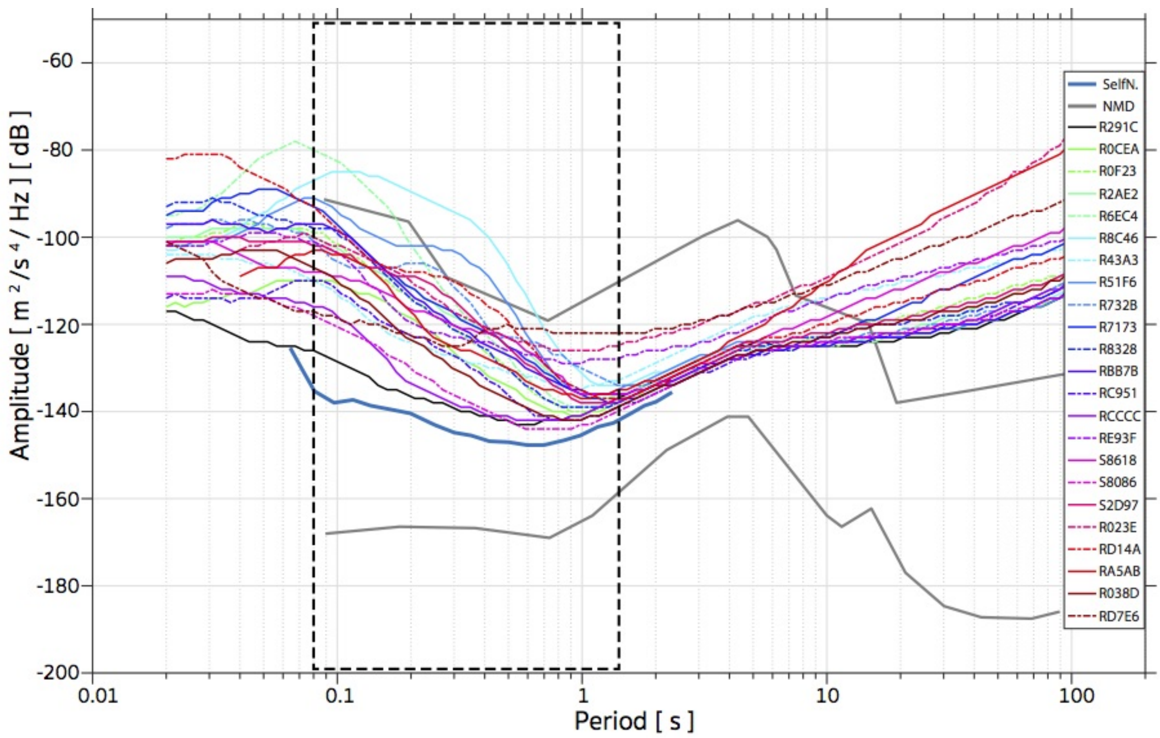


**Figure 4.7:** *Power spectral density probability density function's median value for each NSSN station as a function of period. Thick gray lines are the high and low noise models according to Peterson (1993); McNamara and Buland (2004). For comparison, we also plot the same curve from the test site in Switzerland (R291C), and the instrument self-noise as provided by the manufacturer. The dashed black line highlights the bandwidth of flat instrument response. The curves are constructed using hourly PSDs with 50 % overlap during the period from June to December 2019.*

sources inside the network, but also across Nepal and from regional and teleseismic distances. For earthquakes in Nepal, our reference information comes from the earthquake catalogue published by the NSC, while for more distant events we rely on global catalogues such as the one from the European-Mediterranean Seismological Center (EMSC) and the United States Geological Survey (USGS). Figure 4.8 shows three examples of recorded waveforms, for a local, a regional and a teleseismic earthquake. The arrival of P and S phases is clearly visible, although somewhat different from simplistic theoretical arrival times. For local events, we detect all earthquakes that the NSC publish: these are detected by an STA/LTA-trigger at the NSC network, but only $M_L \geq 4$ events in Nepal are published on their website. The NSSN recorded some regional events in the Hindu Kush region, in China and in Myanmar. Likewise, we have recorded almost all M>7 events around the globe, mostly at thousands of kilometers distance, including in Japan and in Indonesia region. We also clearly identified the Mw8.0 earthquake on 26 May 2019 in Peru at ca. 16'000 km distance. For large events, we clearly observe the more slowly propagating surface waves arriving after the body (P and S) waves. In 6 months of operational time, a total of 194 reported earthquakes have been identified in our records.

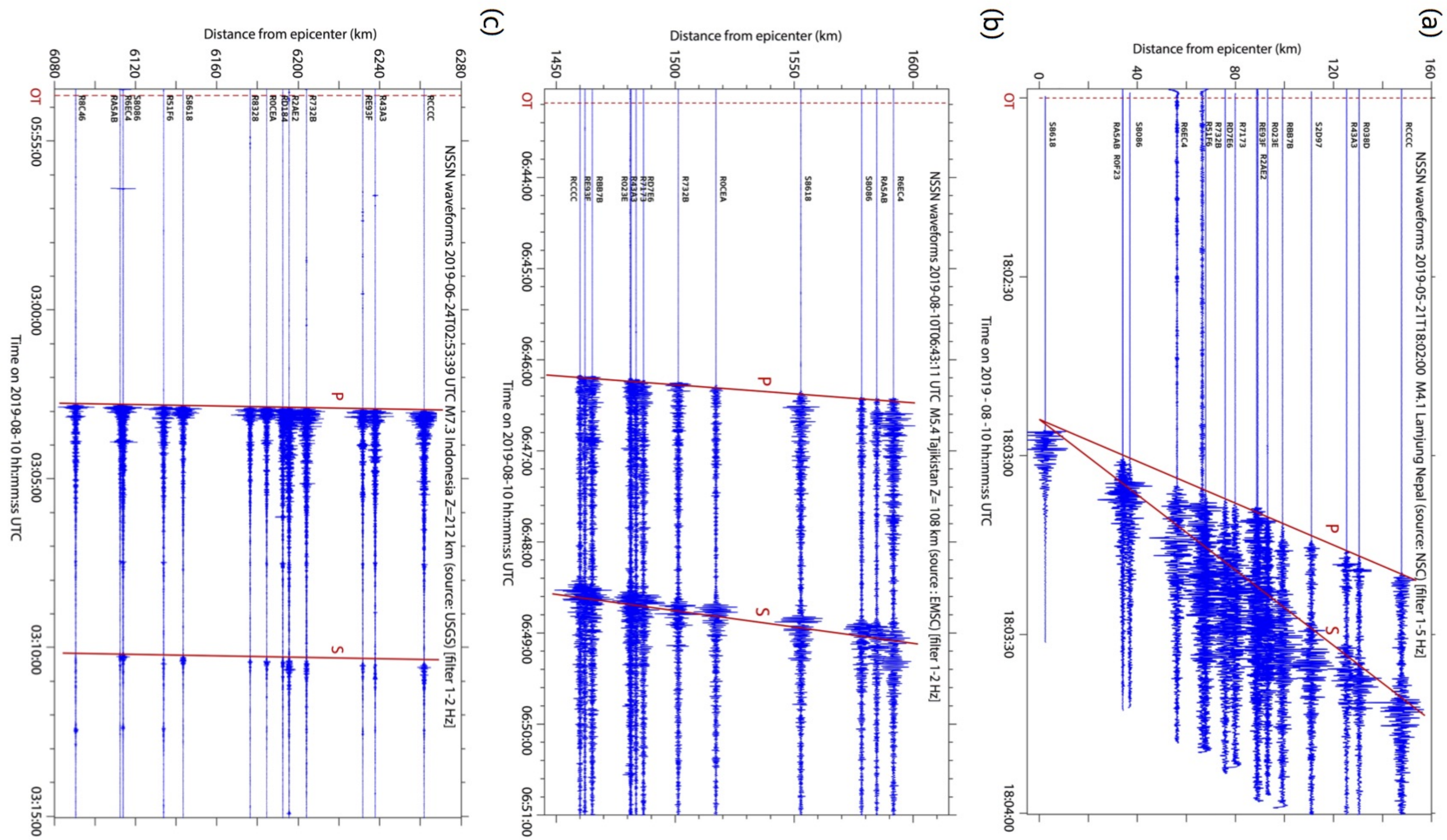


**Figure 4.8:** *Examples of earthquakes' waveforms recorded by the NSSN. The dashed red line in each figure denotes the origin time of the earthquake in the available catalog. (a) Filtered waveforms in the 1 - 5 Hz frequency band of a local event, with solid red lines plotted for the theoretical P and S wave arrival times using local velocity model in Nepal (Pandey et al., 1995). (b,c) Waveforms of a regional event in Tajikistan and of a teleseismic event in Indonesia, filtered between 1 - 2 Hz. Solid red lines are plotted for the theoretical P and S wave arrival time using global iasp91 velocity model (Kennett and Engdahl, 1991). First order information of each event is written on top of each figure, including the source of the information. NSC, National Seismological Centre, Kathmandu; EMSC, European-Mediterranean Seismological Centre; USGS, United States Geological Survey. All waveforms are normalized to the same maximum amplitude.*

In Figure 4.8, the theoretical P and S wave arrival times are plotted on top of the recorded waveforms using different velocity models. We have used local velocity model in Nepal (Pandey et al., 1995) for local earthquakes, iasp91 (Kennett and Engdahl, 1991) for regional and global events. The slope of the theoretical P and S wave arrivals do not exactly fit that of the observed waveforms for the local earthquake, which is probably related to the variation of the local crustal structure with respect to the 1D model. We estimate the origin time of the local event at 18:02:54 UTC, however 18:02 UTC is reported in the published catalogue, the information about the seconds is truncated (Fig. 4.8a). Similarly, P but especially S phases show different arrivals times from the theoretical ones for the regional earthquake in Afghanistan, which again points to more complex velocity model of the orogenic region along the raypath than the 1D model used. For the teleseismic event, the P and S wave arrivals match relatively well the theoretical arrival times.

Some of the events we recorded are felt by the people involved in our school seismology

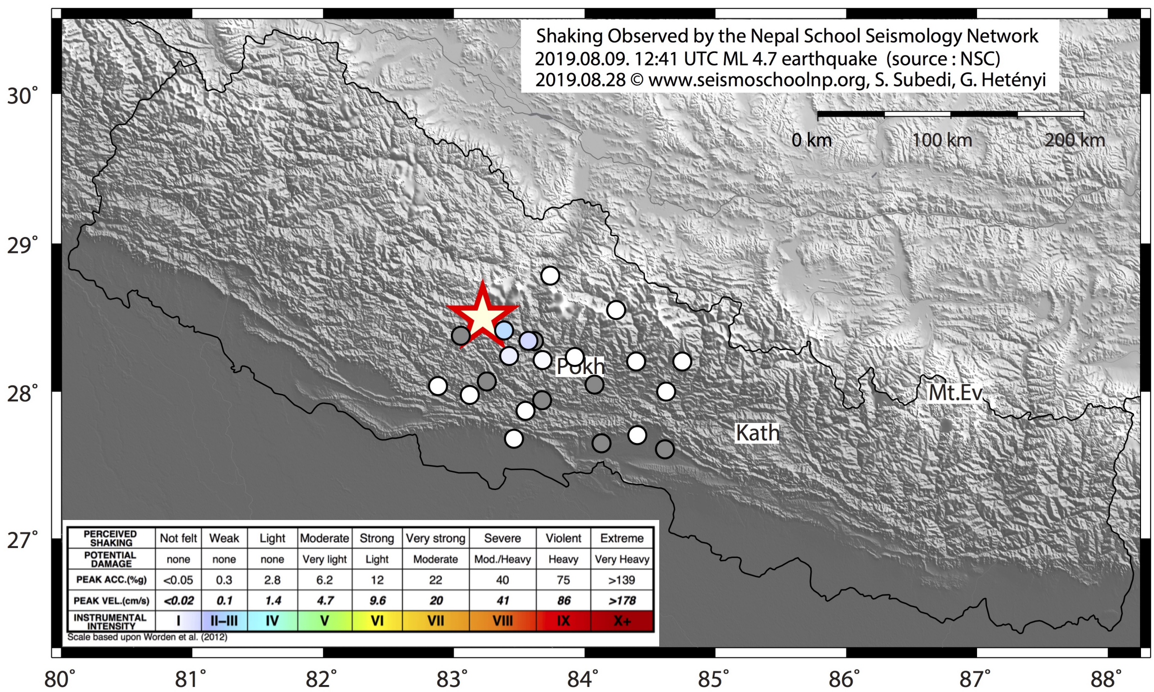


**Figure 4.9:** *Observed instrumental intensity map from the 2019 August 9 $M_L$4.7 Myagdi earthquake. The observed intensity data at NSSN stations are plotted in circles and are color-coded according to their value based on Worden et al. (2012) as shown in the legend. Gray color means no data for the event from that station (either no internet or no power supply). The capital city of Nepal, Kathmandu is denoted by Kath, the highest point of the Earth, Mount Everest is denoted by Mt.Ev, and the capital city Pokhara of the Gandaki province is denoted by Pokh.*

program, who were naturally interested to learn more. For that purpose, it is very instructive to produce instrumental intensity maps that shows measured intensity values at stations across the NSSN. We produce such maps routinely for felt events in the study area, and represent shaking as instrumental intensity converted from peak ground velocity (which in our sensors is recorded on the vertical component, hence we note it $PGV_V$), following the scale of Worden et al. (2012). The instrumental intensity map for the event causing one of the largest intensities so far, an $M_L$4.7 earthquake inside the network is presented in Figure 4.9. The station closest to the epicenter, *Janapriya Secondary School, Darwang*, Myagdi district, clearly felt the shaking with an intensity of II-III, while stations further from the epicenter have not recorded felt-shaking (intensity I). The largest $PGV_V$ measured so far was recorded very close to a $M_L$4.5 event, at a value of 1.22 mm/s. The instrumental intensity map will not be delivered for large events as the sensors will reach their limits of recording (clip) (Anthony et al., 2019) at 22 mm/s (peak-to-peak) according to the manufacturer. Nevertheless, the micro- to moderate size seismicity can be very well monitored. In general, the instrumental intensity map representing measured shaking is critical to estimate the damage after an earthquake and to prepare an emergency response and rescue; in the frame of our educational seismology project, it shows all schools together and demonstrates the connection within the community of schools.

### 4.5.3 Seismology: detection threshold

By collecting detected phase arrivals from a representative number of earthquakes, the detection threshold of the RS1D in real field conditions can be mapped. This strongly depends on the selected sites, and here we present our findings (Fig. 4.10).

At the test site in Switzerland, which is relatively quiet, we are able to record relatively small earthquakes ($M_L$<1.0) earthquakes at surprisingly large (50 km) distances. This was possible as the background noise level of this site is low, typically around 0.2 $\mu$m/s or less. The observed peak ground velocity ($PGV_V$) for all events recorded at this site is plotted as a function of epicentral distance and magnitude in Figure 4.10a. Observed ground velocity increases with magnitude and decreases with distance, as expected. Still, typical felt ($M_L \sim 2.5$) events are detected up to ca. 300 km distance.

In Nepal, information on micro earthquakes ($M_L$<4.0) is not publicly accessible. Nevertheless, all reported local earthquakes of this size and larger are clearly recorded, and also some regional events of $M_L$ 4 beyond 1'000 km distance have been detected (Fig. 4.10b). The magnitude and distance dependence of $PGV_V$ show the same pattern as for the test site: increasing with the magnitude, decreasing with the distance when other parameters are kept constant. The list of earthquakes used in this study is provided in the Table 4.3. The location of micro earthquakes inside the NSSN is currently being investigated, and is beyond the scope of this article.

| S.N. | Date | Time (UTC) | Latitude (°N) | Longitude (°E) | Magnitude ($M_L$) |
|---|---|---|---|---|---|
| 1 | 2019-04-24 | 00:44 | 27.69 | 85.17 | 5.2 |
| 2 | 2019-04-24 | 00:55 | 27.70 | 85.14 | 4.3 |
| 3 | 2019-04-29 | 05:50 | 27.93 | 85.94 | 4.0 |
| 4 | 2019-05-04 | 02:52 | 27.94 | 85.72 | 4.0 |
| 5 | 2019-05-11 | 18:51 | 28.98 | 81.78 | 5.1 |
| 6 | 2019-05-17 | 08:23 | 27.85 | 84.87 | 5.0 |
| 7 | 2019-05-21 | 18:02 | 28.21 | 84.37 | 4.1 |
| 8 | 2019-05-25 | 15:23 | 29.50 | 81.28 | 4.3 |
| 9 | 2019-05-25 | 05:17 | 27.70 | 86.47 | 4.9 |
| 10 | 2019-05-30 | 04:16 | 29.62 | 82.11 | 4.6 |
| 11 | 2019-06-14 | 06:37 | 29.52 | 81.05 | 4.0 |
| 12 | 2019-06-15 | 15:47 | 28.95 | 81.98 | 4.5 |
| 13 | 2019-06-27 | 16:36 | 27.95 | 84.80 | 4.0 |
| 14 | 2019-07-06 | 10:30 | 27.67 | 85.42 | 4.6 |
| 15 | 2019-07-24 | 12:13 | 27.80 | 86.15 | 4.2 |
| 16 | 2019-08-09 | 12:41 | 28.50 | 83.22 | 4.7 |
| 17 | 2019-08-14 | 17:24 | 27.69 | 86.26 | 4.3 |
| 18 | 2019-08-22 | 01:22 | 27.52 | 86.39 | 4.0 |
| 19 | 2019-09-15 | 05:09 | 30.30 | 81.74 | 5.0 |
| 20 | 2019-09-16 | 14:33 | 29.80 | 80.48 | 4.4 |
| 21 | 2019-09-17 | 04:08 | 28.21 | 84.49 | 4.5 |
| 22 | 2019-09-21 | 00:34 | 28.15 | 84.61 | 4.0 |
| 23 | 2019-09-22 | 16:16 | 28.25 | 84.49 | 4.4 |
| 24 | 2019-09-25 | 19:33 | 27.71 | 86.32 | 4.0 |
| 25 | 2019-09-26 | 13:04 | 28.28 | 84.65 | 4.7 |
| 26 | 2019-09-28 | 04:58 | 30.00 | 81.45 | 4.3 |
| 27 | 2019-09-29 | 01:42 | 28.66 | 83.06 | 4.4 |
| 28 | 2019-10-20 | 19:24 | 27.82 | 87.98 | 4.2 |
| 29 | 2019-10-22 | 05:21 | 26.88 | 86.59 | 4.1 |
| 30 | 2019-10-28 | 13:42 | 29.66 | 82.04 | 4.1 |
| 31 | 2019-10-31 | 22:06 | 28.45 | 83.23 | 4.5 |
| 32 | 2019-11-12 | 02:00 | 30.20 | 80.10 | 4.6 |
| 33 | 2019-11-19 | 13:30 | 29.42 | 81.10 | 5.7 |

**Table 4.3:** *List of earthquakes in Nepal (as provided by the NSC) used for the magnitude calibration equation computation in this study. Depth information is not published on the NSC webpage.*

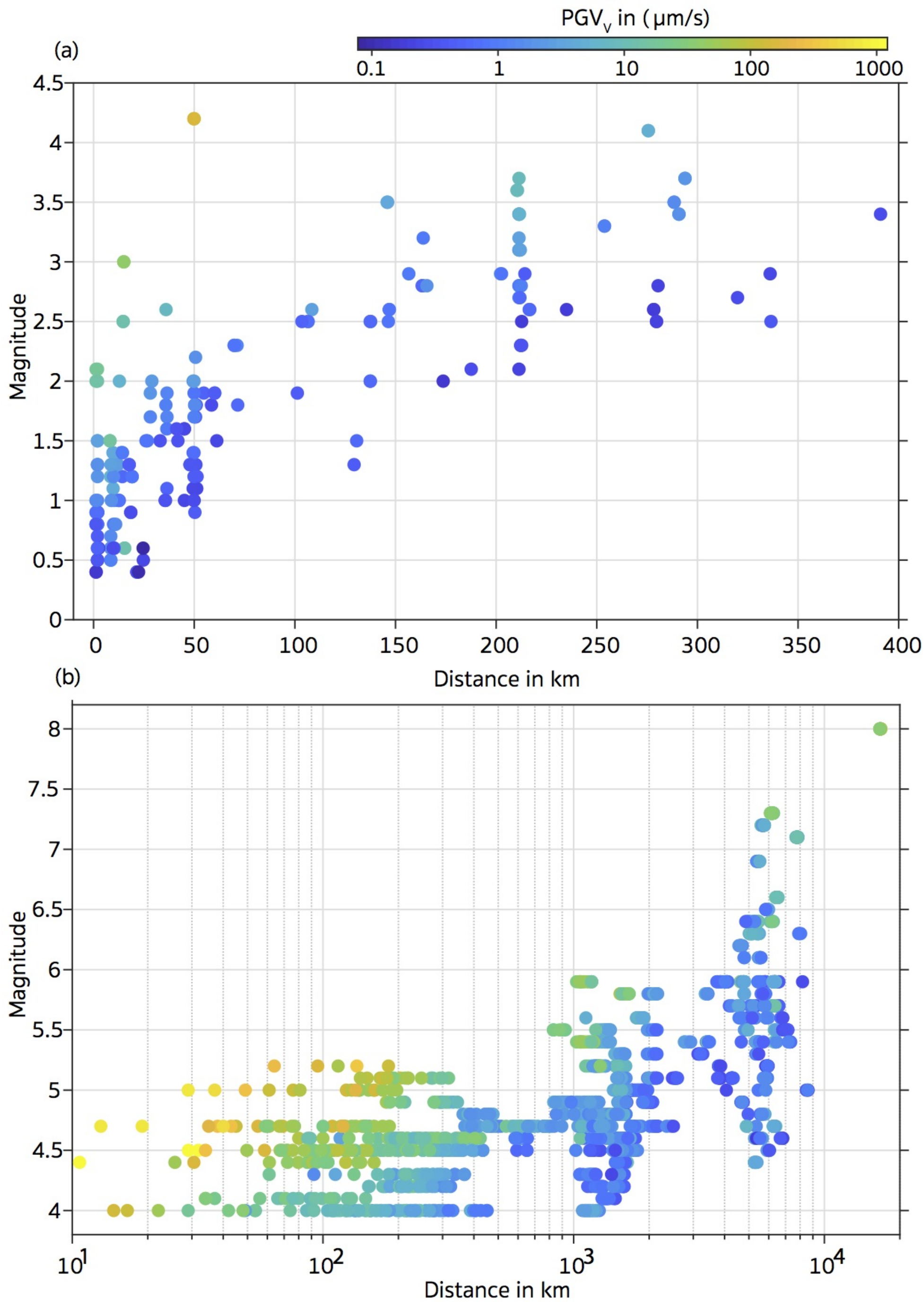


**Figure 4.10:** *Observed vertical peak ground velocity ($PGV_V$) as a function of magnitude and distance at (a) our test site in Grimisuat, Switzerland, and (b) across the NSSN. Each circle in the plot represents the observed maximum amplitude motion at a station following a single earthquake. In total 210 events for the station in Switzerland and 194 events for NSSN are plotted using the 6-month data from the catalogs. Sources of earthquake catalogs: SED in Switzerland (a), NSC and USGS for stations in Nepal (b).*

### 4.5.4 Seismology: magnitude calibration for earthquake monitoring

An important parameter in seismology is the magnitude of an earthquake. Due to various definitions of magnitude, it is not always straightforward to compare one event measured on one scale with another event measures on another scale. Typically, local magnitudes $M_L$ for a given region are converted to moment magnitude Mw for an energy based comparison. In Nepal, $M_L$ is provided by the NSC, and for coherency with the nationally used scale, we here quantitatively calibrate our own seismic observations to fit that scale.

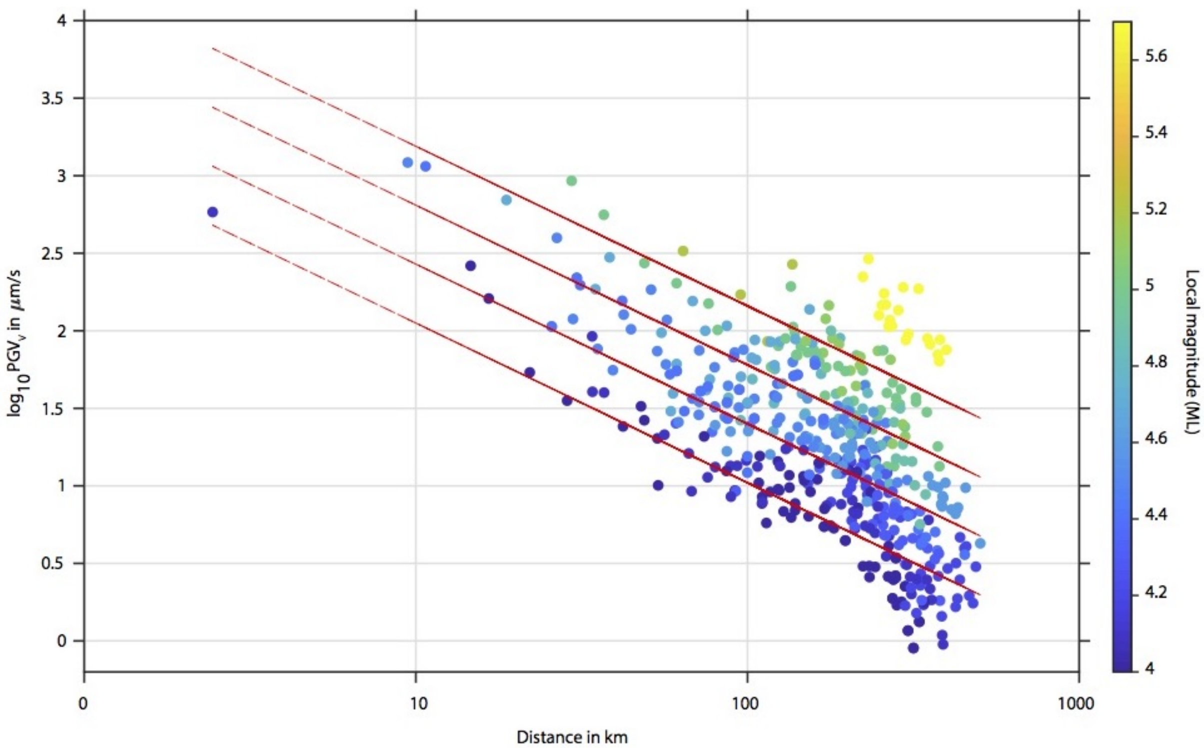


**Figure 4.11:** *Observed peak ground velocity ($PGV_V$) across the NSSN as a function of earthquake magnitude and epicentral distance. Each circle in the plot represents a single earthquake detection at a station, colored by magnitude. Six months data are considered from April 2019. Source of earthquake data is the National Seismological Center's published catalog. Red lines represent the fitted $PGV_V$ - distance lines for M4.0, M4.4, M4.8, and M5.2 earthquakes after the regression (see text for details).*

Our approach is based on the presented by (Allen et al., 2012) who fit a general equation on intensity and how it attenuates with epicentral distance and earthquake magnitude. Our mathematical approach is the same, but instead of intensity values, we work with vertical-component peak ground velocity $PGV_V$, in $\mu$m/s. Following Allen et al. (2012), we assume the following formula:

$$log_{10}(PGV_V) = a + b \times M_{NSSN} + c \times log_{10}(D) + S \quad (4.1)$$

where $M_{NSSN}$ is the local magnitude determined by the NSSN, $D$ is epicentral distance in kilometers, and $S$ is a site effect term which we first consider to be 0. The value of $PGV_V$ at each station is determined as the maximum amplitude recorded by a vertical-component low-cost seismometer, typically of the Sg or Sn seismic phase, after second-order Butterworth band-pass filtering between 0.7 - 7 Hz. The three constants $a$, $b$ and $c$ are the parameters we have to determine by regression. Once the values are known, we can rearrange the equation to compute $M_{NSSN}$ as a function of observed $PGV_V$ and $D$:

$$M_{NSSN} = (1/b) \times log_{10}(PGV_V) - (c/b) \times log_{10}(D) - (a/b) \tag{4.2}$$

The full observed dataset is presented in Figure 4.11. For the regression, we considered events located by the NSC in the distance range 31 - 450 km (within Nepal), and we omit the single $M_L$5.7 event as it is 0.5 magnitude units away from the rest of the dataset. Events having epicentral distances smaller than 31 km (i.e., log10(D) < 1.5) have not been considered to avoid near - source effects and because of uncertain focal depth determinations. Then, for each 0.1 - wide bin of earthquake magnitude (including overlap as catalogue magnitudes are rounded to the nearest 0.1 unit), we regress for the intermediate distance intensity attenuation value, $c$, and obtain the results shown in Figure 4.12a. The median value of this dataset, trimmed by $1\sigma$ around the raw mean value, is taken as the most fitting attenuation value $c$. The value turns out to be $-1.03$, and since no clear trend of variability is observed with magnitude, it is used as a constant for further regression analysis.

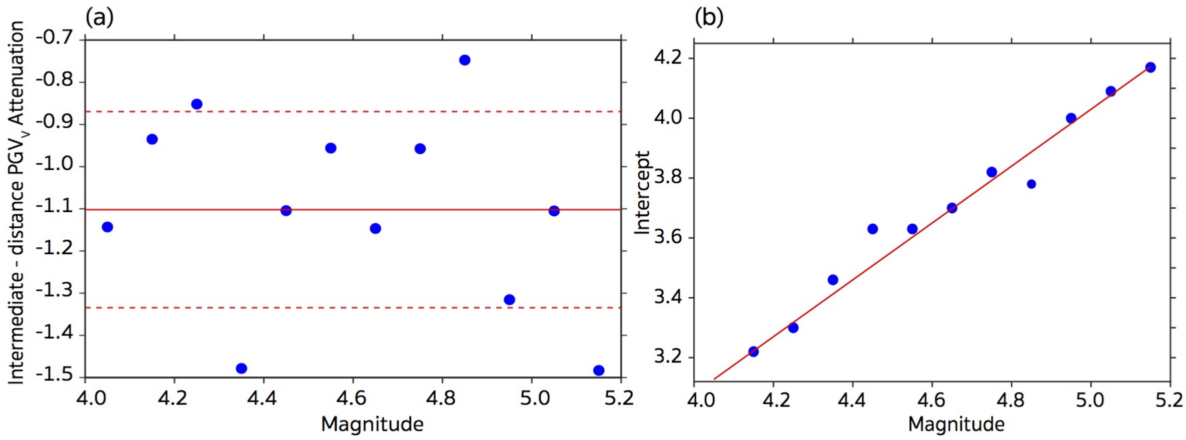


**Figure 4.12:** *(a) Intermediate-distance $PGV_V$ attenuation c plotted for magnitude bins. Data points beyond the $1\sigma$ variability (0.30, red dashed lines) of the raw mean ($-1.39$, solid red line) are trimmed and the median of the remaining $PGV_V$ attenuation provided parameter c in Eq. 4.1, which is found to be $-1.03$ across the dataset. (b) Fitting the distance and $PGV_V$ data for each magnitude window using the constant slope value c to find the slope and intercept of the magnitude dependence (respectively b and a in Eq. 1), regressed using the linear least squares.*

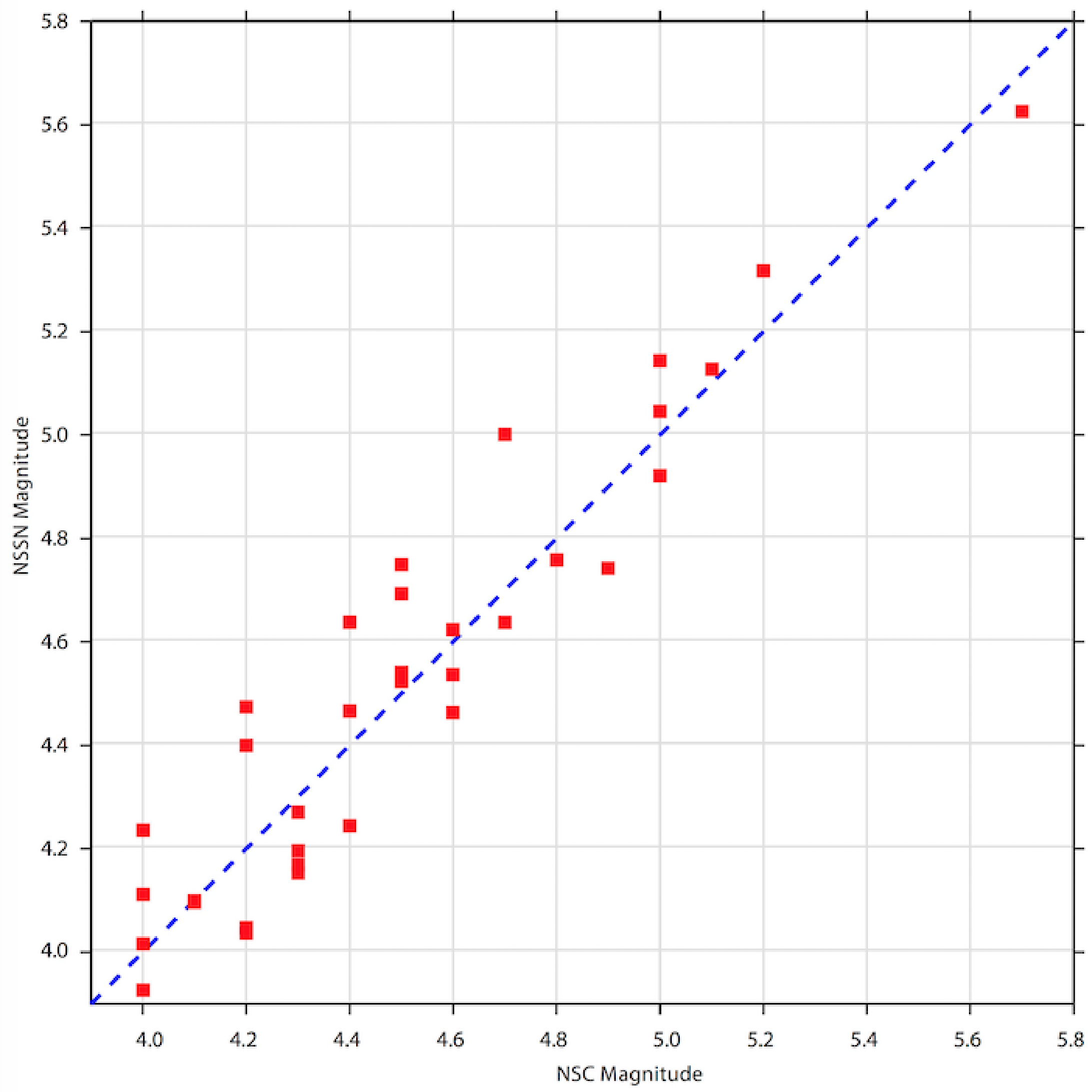


**Figure 4.13:** *Magnitude comparison plot. The NSC-reported magnitude is plotted against the NSSN magnitude using the newly calibrated magnitude equation (Eq. 4.3). Note that the site effect at each NSSN station is considered as described in the text. The maximum difference between the two magnitude scales for any given event is <0.3 unit of* $M_L$.

In a second step, in order to find the values of the slope $b$ and intercept value $a$ of the magnitude dependence in Equation 4.1, we have fitted the PGV − distance data for each magnitude window using the constant slope value $c$ and regressed using the linear least squares (Figs 4.12b and 4.11). The values we find are $a = -0.72$ and $b = 0.95$. (The same calibration including the $M_L$ 5.7 event gives slightly different values for $a$, $b$ and $c$: as −0.53, 0.94 and −1.10, respectively, but the change in $M_{NSSN}$ is negligible, $< 0.1$.)

Hence, replacing these into Equation 4.2, we obtain the calibrated magnitude equation for the NSSN:

$$M_{NSSN} = 1.05 \times log_{10}(PGV_V) + 1.08 \times log_{10}(D) + 0.75 \tag{4.3}$$

Finally, using the determined value of $a$, $b$ and $c$ and Equation 4.1, we have estimated theoretical values of $PGV_V$ for each event and each station. By subtracting this from the observed $PGV_V$ values for all events, the average residual of $PGV_V$ is calculated for each station, which is effectively gives the site effect term $S$. As the nominal sensitivity of the RS1D sensors is provided with a 10 % uncertainty, we have considered the value of $S$ in Equation 1 for a station only when its value exceeded 0.1 (10 sites, largest value 0.29). With this value, we can correct the observed value of $PGV_V$ when computing $M_{NSSN}$ in the future.

To assess and to appreciate the magnitude calibration equation, we plot the NSSN - observed magnitude value against the local $M_L$ as provided by the NSC in Figure 4.13. The largest difference is below 0.3 units, which is a very reasonable value considering that the value of $b$ (magnitude $-$ dependence of $PGV_V$) is on the order of 1, and that network-wide determined magnitude values are averaged from individual station magnitudes with a standard deviation that can exceed this difference. Although the magnitude equation was calibrated using data from $M_L$ 4.0 - 5.2 earthquakes, the fit to the so far single $M_L$ 5.7 event is very good.

Although the seismometers in the NSSN are relatively inexpensive, this program for schools allowed us to build a network with real observatory capabilities for seismic monitoring. This somewhat unexpected point further highlights the very important role that schools and their environment can play in monitoring, understanding and preparing for earthquakes.

## 4.6 Conclusions

In less than two years of work, we have established the framework of the Seismology at School in Nepal program, and successfully implemented it in the field. The program carries both educational and seismological aspects, results of which can be summarized as the following:

- The program jointly established an educational network with the close involvement of 22 schools, each hosting a low-cost seismometer which spans the Nepal School Seismology Network in the region where a great earthquake is due.
- Various educational activities were performed, involving schools, students, teachers and communities in earthquake education; teachers were trained primarily during a 2-day dedicated workshop.
- With only six months of data, useful seismological results could be produced for both education (record sections, shake-maps) and research (event detectability).
- A new local magnitude equation for Nepal is calibrated based on the data observed by

the NSSN, which is applicable to consistently compute the magnitude of forthcoming local events.

- Openly available data and educational resources through our program's website contribute to the broadest possible outreach.

On the basis of our bottom-up approach, earthquake preparedness and earthquake awareness have increased in the local communities. In this sense, the project has started to help this region of Nepal to prepare for future earthquakes, and we hope that the initiative is spread to other regions of Nepal.

## 4.7 Acknowledgement

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# Chapter 5

# Impact of an educational program on earthquake awareness and preparedness in Nepal

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*Geosci. Commun. Discuss, 2020. doi:10.5194/gc-2020-25*

## 5.1 Abstract

Scientific education of local communities is key to help in reducing the risk associated with natural disasters, such as earthquakes. Western Nepal has a history of major seismic events and is highly prone to further earthquakes; however, the majority of the population is not aware about or prepared for them. To increase earthquake awareness and improve preparedness, a seismology education program was established at 22 schools in Nepal. In each school, educational activities were performed by teaching earthquake related topics in classrooms, offering training to teachers and through installing a low-cost seismometer network which supported both teaching and awareness objectives. To test the effects of this program we conducted two surveys with school children, one before and one after the initiation of the program, with several hundred participants in each. The survey findings highlighted that educational activities implemented at schools are effective in raising awareness levels of children, promoting broader social learning in the community, thus improving the adaptive capacities and preparedness for future earthquakes. However, perceptions of risk did not change very much. The high and positive impact of the program on the students and the community is encouraging in the continuation and expansion of the program.

## 5.2 Introduction

It is becoming increasingly important to educate people in the era of global change about environmental hazards to ensure they are well prepared to face the rising number of challenges. Education may play a central role for the risk management of natural hazards and help to reduce vulnerability and improve adaptability though allowing people to anticipate and prepare for hazards (Godschalk, 2003; Renn and Graham, 2005).

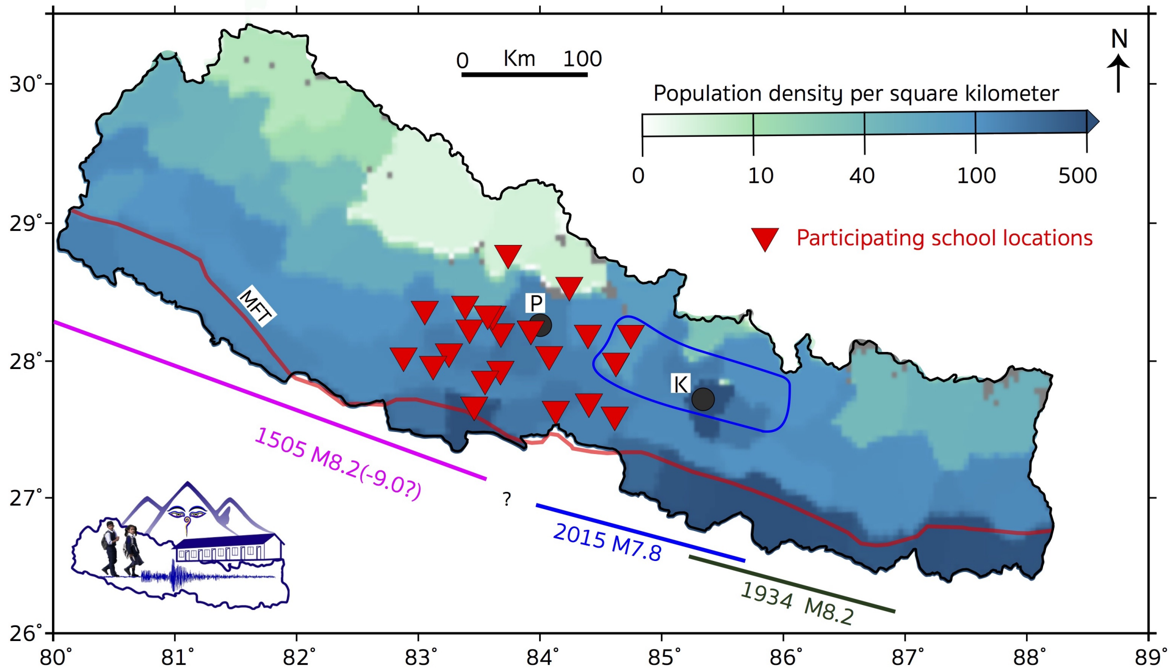


**Figure 5.1:** *Map of Nepal, with the locations of schools participating in the Seismology at School in Nepal program. Background color is population density data (CIESIN and CIAT, 2005). The Main Frontal Thrust (MFT), the surface trace of the fault underlying most of Nepal and hosting all great earthquakes in the region, is indicated in red solid line. Three colored segments represent the rupture extent of the corresponding major and great earthquakes with magnitude (M) as indicated after Bollinger et al. (2016). For the 2015 Gorkha earthquake the rupture area is also plotted (blue contour). Letters P and K refer to cities Pokhara and Kathmandu, respectively, marked with black circles.*

Exact earthquake prediction is currently not possible, but responses to such events can be prepared for in advance to mitigate the effects they can have on society and human well-being (Turner, 1976). The impacts of earthquake disasters can be minimized by learning what to do before, during and after earthquakes, and by taking a variety of personal safety measures (Lehman and Taylor, 1987). Whether people prepare for future earthquakes or not can be significantly influenced by their education and their engagement in the topic (Tanaka, 2005). All-inclusive public awareness and education is fundamental to reducing causalities, personal injuries, and property damage from natural disasters (National Research Council and others, 1991; Torani et al., 2019). Researchers can contribute and play a key role in the education of society; not just to engage more people in research, but also to provide scientific explanations for natural hazards and related consequences to local communities as well as helping to develop polices for mitigation of the effects.

**Figure 5.2:** *Students gathered at the morning assembly in the Shree Himalaya Secondary School, Barpak, Gorkha district. The school building was damaged during the 2015 earthquake and students were in temporary shelters. The construction of the new building is visible on the top of the picture. (Photo: S. Subedi, in May 2018, with permission of the school).*

Earthquakes are the most common and deadliest natural hazard in Nepal with a long history of impacts in the country (Bollinger et al., 2016). Historical records indicate that many houses and temples in Nepal collapsed during the 1255 earthquake, and one third of the population including the King, Abhaya Malla, was killed. There are also records of an earthquake with a moment magnitude $> 8$ in 1505 (Ambraseys and Jackson, 2003) and indications that even larger earthquakes are plausible in the Himalayas (Stevens and Avouac, 2016). In 1934, during an earthquake (Fig. 5.1) with a moment magnitude (Mw) of 8.2 over 8'500 people lost their lives, 200'000 houses were severely damaged and more than 80'000 buildings completely collapsed (Dixit et al., 2013).. The most recent major earthquake (Mw 7.8), in 2015, hit central Nepal resulting in about 9'000 causalities, and nearly 800'000 buildings were damaged or destroyed, leaving millions of people homeless. The resulting losses were equivalent to 50 % of total national GDP (Chaulagain et al., 2018). In addition, 19'000 classrooms were destroyed and 11'000 damaged (NPC, 2015). It is suggested that if people had better awareness, preparations could have been more adequate and the negative impacts might have been reduced (Hall and Theriot, 2016).

In Nepal, the National Seismological Center under the Department of Mines and Geology has been conducting seismic monitoring since 1978. The Department of Education is responsible for developing different educational activities across the nation, and the Department of Urban Development and Building Construction has been working for building codes design and implementation. After the 2015 earthquake, the National Reconstruction Authority was established and works towards the reconstruction of buildings damaged during the Gorkha earthquake. Despite these efforts, the topic of earthquakes is not included at any level of the official school curriculum in the Nepali education system. However, recently the National Society for Earthquake and Technology (NSET) initiated the Public-School Earthquake Safety Program in Nepal, but only in a few districts of the country (Dixit et al., 2014). This program focuses mainly on the retrofitting of school buildings to restore and minimize future damage following the 2015 earthquake; however, educational efforts are still very limited.

Following the devastating 2015 Gorkha event, and considering the history of major earthquakes and the likelihood of many more, as well as poor educational efforts on the topic, we initiated and implemented a seismology education program in schools in Western Nepal (Fig. 5.1 and also Chapter 4, Subedi et al., 2020) including the area affected by the 2015 earthquake and expanding towards the West (Fig. 5.2). The aim of the program is to increase the earthquake awareness levels in Nepal, starting from the schools, with the hope that this knowledge will be spread into the community through social learning, and partly through the establishment of a low-cost seismic network (Figs. 5.1, 5.3). In this study, the effects of the education program for earthquake awareness and preparedness are evaluated. The evaluation was performed by collecting data from students through two surveys, one before and one after the initiation of the education program.

## 5.3 Methods

The data for this study were collected using two questionnaire surveys on paper, conducted in Nepali language: in 2018, before the initiation of the education program, and in 2020, nearly a year after the full implementation of the program.

Before the initiation of the education program, we undertook fieldwork to help inform our strategy and the educational materials, and to ensure the education program was well adapted to the Nepali education system. In 2018, during the first visit to schools, we talked with the school leaders about the program and its benefits, and gave sample lectures (ca. 1-2 hours including questions) to students between the ages of 14-16, providing key information on earthquakes. Before the sample lecture and in each school, students were requested to complete in a paper questionnaire survey on earthquake related questions. In special lectures we also taught students how to prepare before an earthquake, how to save lives during


**Figure 5.3:** *Left: The Raspberry Shake 1D low-cost seismometer, installed in 22 schools across Central Nepal (Fig. 5.1). Right: Earthquake awareness sticker, as a reminder, in English and Nepali language (artwork of M. Dessimoz). The sticker image is available for download from our program's webpage: www.seismoschoolnp.org.*

an earthquake, and what to do after an earthquake. We also provided a flyer containing detailed information and pictures (Fig. 5.4), of which we distributed 500 copies. Similarly, we designed a sticker to remind people about earthquake hazards (Fig. 5.3), and distributed this to students and teachers (3'000 so far).

In April-May 2019, during the second school visit, the program was fully implemented with the installation of an educational, low-cost seismometer in every school. The seismometer's record is displayed on a computer, which is easily accessible to students in their physics class, or through an online application. During the visit, we also identified the open place near the school where students should meet in case of earthquake and installed an Emergency Meeting Point sign in Nepali. To increase the efficiency of the learning and to ensure long-term uptake, we organized a 2-day workshop for nearly 100 school teachers, which was very well received. The full details of the program are documented in an earlier paper (Subedi et al., 2020) and all the material is accessible on the program website (www.seismoschoolnp.org).

In this article, we focus on evaluating the efficiency of our program in terms of the knowledge and behavior change of students related to earthquakes. Out of 22 schools participating in the program, 15 schools were chosen for the survey, covering a range of socio-economical contexts. Students for the surveys were selected randomly from grades 9 and 10, representing the 14-16-year-old age group. The total number of responses collected was 318 in 2018 and 480 in 2020, respectively. For logistical reasons, some responses in the pre- and post-survey (27 %) came from different schools, but this is not expected to affect the results as they were independent samples. While the first set of students surveyed had received no earthquake education whatsoever, those who filled out the second survey were exposed to information and


**Figure 5.4:** *Educational flyer in Nepali language on what to do before, during and after an earthquake. The flyer has been translated and adapted from an English version, compiled by and available from the CPPS earthquake education centre in Sion, Switzerland (www.cpps-vs.ch). The Nepali flyer is available for download from our program's webpage: www.seismoschoolnp.org.*

lectures frequently about earthquakes from the teachers who were trained in our program.

When the exact same question was asked before and after our program's implementation, we quantify the change using $\chi^2$ test analysis. In doing so, our null hypothesis $H_O$ is that our program had no effect on the students. If this null hypothesis is unconfirmed (i.e., the $\chi^2$ value is above the threshold for the corresponding number of possible answers, and the respective p-value is below 5 %), then we interpret that the program had an effect on the students as their answers show a clear, statistically significant change. The complete set of questionnaires are available in the Supplementary materials file of published paper.

## 5.4 Results

The first measurement of this study, performed in the 2018 survey, was about the experience of the 2015 Gorkha earthquake. The majority of respondents, 94 %, felt the shaking. As the earthquake was on Saturday, schools were closed and students were at home; 71 % of students answered that they ran out of a building, and only 15 % hid under a table, 8 % did not know what to do, 3 % stood next to the wall or the doorframe, 3 % had other reactions.

### 5.4.1 Knowledge about the causes and possibility of earthquakes in Nepal

Before the implementation of the program, 7 % students believed that earthquakes were caused by a moving fish carrying the Earth (a Hindu belief and myth). However, 64 % still chose the correct scientific answer: plate tectonics. The majority of students, 84 %, chose the "plate tectonics" answer in 2020, and the percentage of responses relating to the cultural/religious reasons dropped to 2 % (Fig. 5.5).

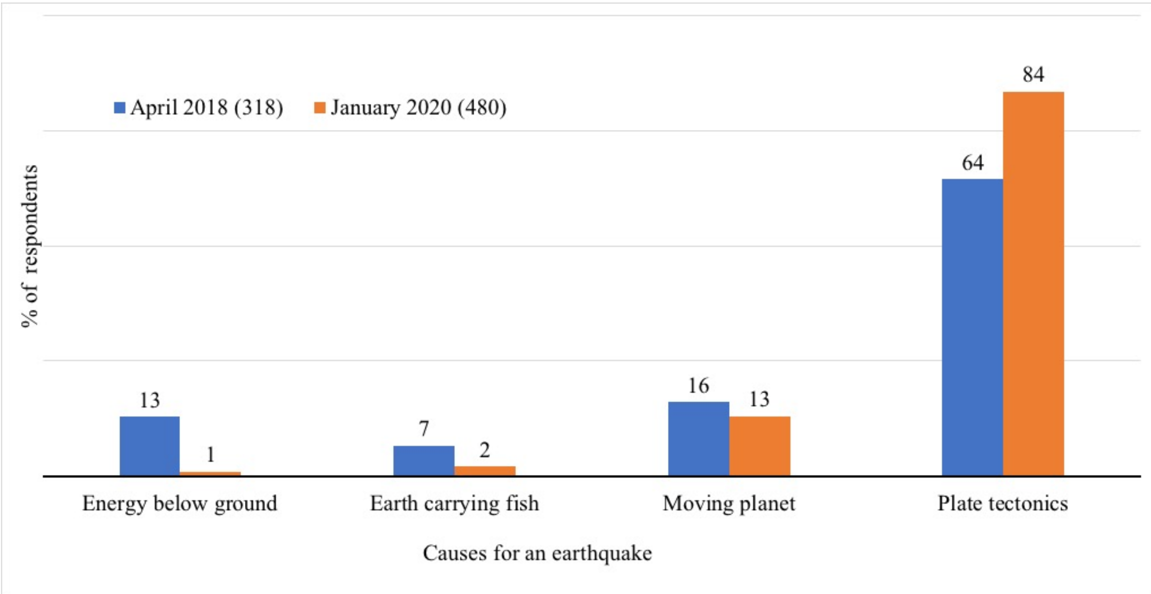


**Figure 5.5:** *Student opinions on what causes earthquakes (Q1), before and after the initiation of our education program. ($\chi^2$ = 78.15, p-value = < .00001, the change is significant).*

Regarding the probability of a future earthquake greater than in 2015, more students knew that such an earthquake in their region was quite likely after the education program (Fig. 5.6a). At the same time, there was a clear drop in the number of responses for very unlikely (17 % in 2018 to 5 % in 2020) and a slight drop in the percentage answering that a future great earthquake is impossible.

Relating to the effects of a Mw > 8 earthquake, after the program, the answer I could die has increased by a factor of 1.8, and all other answers ( *I could be buried alive, I could get hurt, I could lose friend and My home could collapse*) are increased by a factor of at least 1.3 compared to 2018 (Fig. 5.6b; multiple answers were possible).

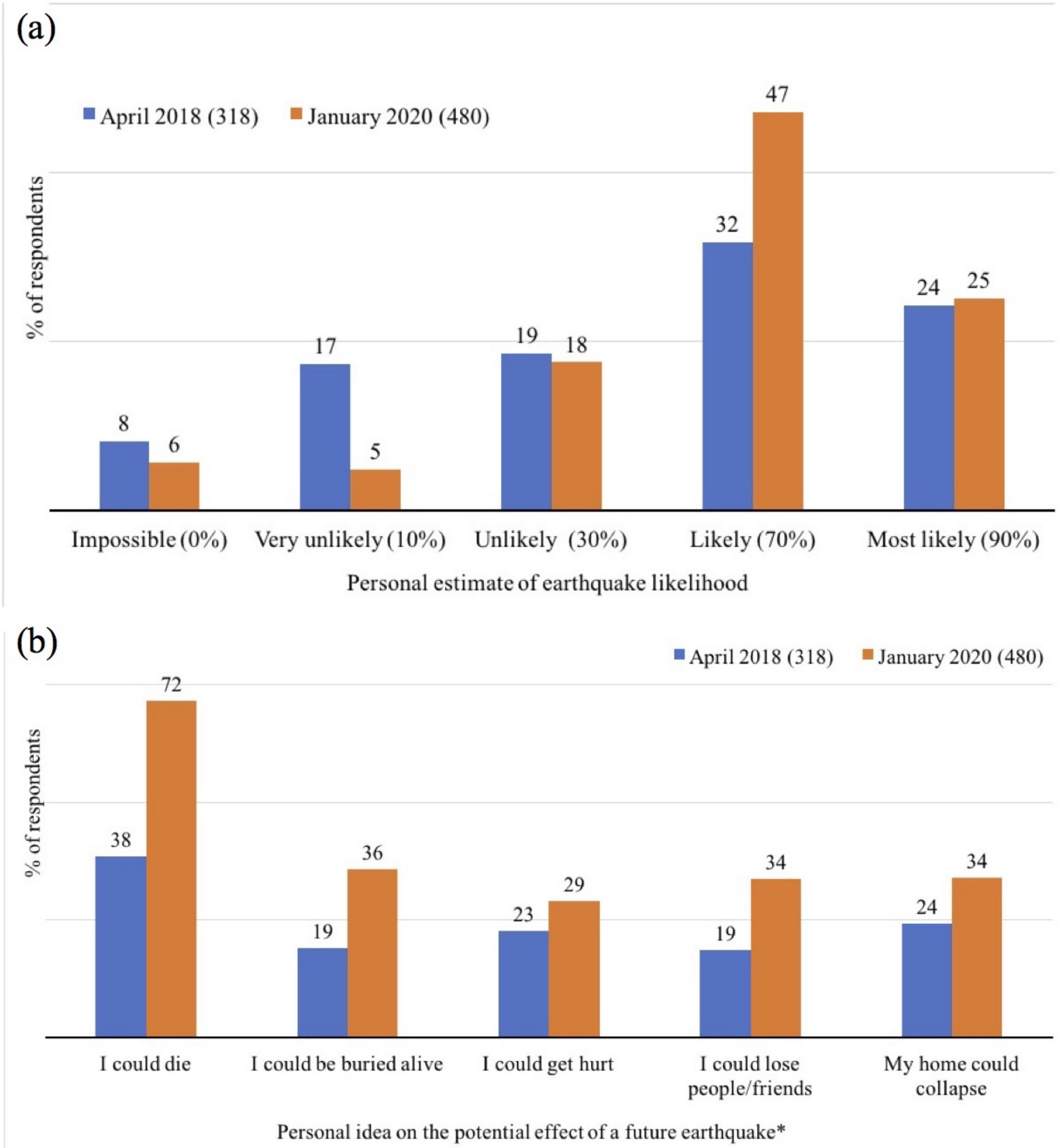


**Figure 5.6:** *(a) Student views on how likely the occurrence of a next earthquake bigger than the 2015 Gorkha earthquake is (Q3), before and after the initiation of our education program. ($\chi^2$ = 43.59, p-value = < .00001, the change is significant). (b) Student answer on the outcome of a potential M>8 earthquake in Nepal (Q2), before and after the initiation of our education program. *Multiple answers were possible.*

In 2018, 31 % students answered they know when an earthquake will occur, which is reduced to 11 % in 2020. The answer itself is not true, and this mis-information could drive people to incorrectly prepare for or act during an earthquake. While our efforts clearly decreased this mis-conception among the students, we could not yet reach each and every student to teach them about the unpredictability of earthquakes. The students' answer agreeing on the impossibility of preventing an earthquake was 86 % in 2020, showing an absolute increase of 18 % from 2018. This question also shows that by 2020, more than double of the respondents have participated in disaster risk education training compared to 2018 (Fig. 5.7).

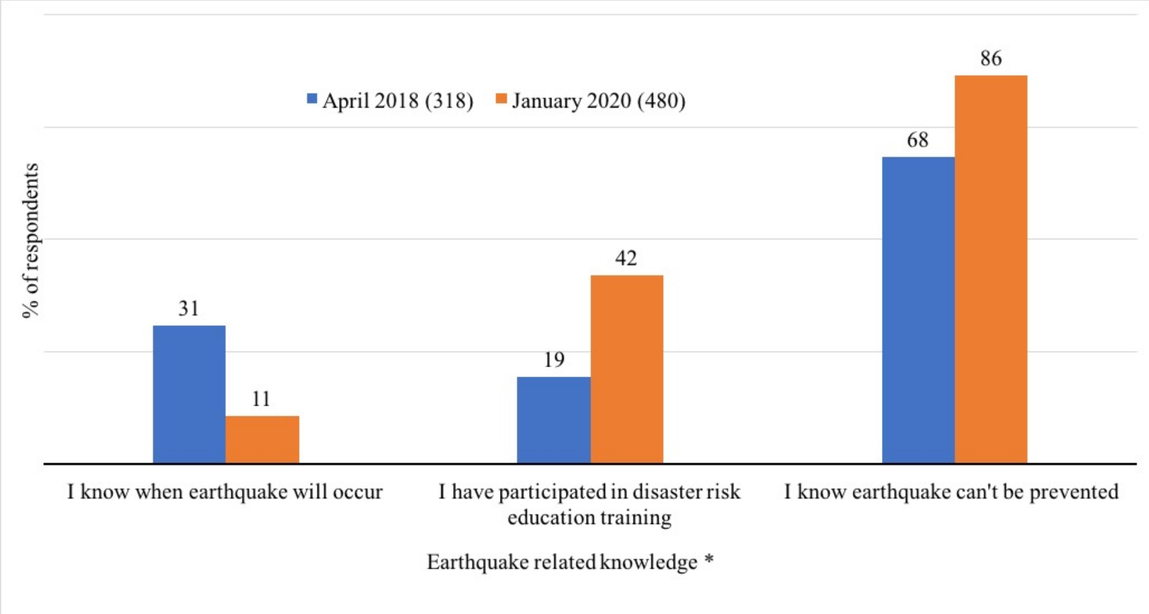


**Figure 5.7:** *Students' personal knowledge about earthquakes (Q13), before and after the initiation of our education program. *Multiple answers were possible.*

### 5.4.2 Knowledge and perceptions about how to behave during and after an earthquake

Three quarters (75 %) of students in 2020 responded that their family knew what to do and where to go during an earthquake, an increase of 55 % from 2018. Only 37 % of students in 2020 believed that their home could resist a large earthquake. For comparison, 65 % students were scared and 22 % panicked during the Gorkha earthquake in 2015 (10 % had calm reactions, 3 % did not care) according to answers in 2018.
In 2018, 62 % respondents didn't know that they should not call others after an earthquake to leave the phone lines available for rescue operation, but in 2020 nearly 80 % students knew this useful practical point (Fig. 5.8).
After the implementation of our program, 65 % of the students believed that they could survive if a large earthquake occurred at night, whereas 43 % felt they could survive in 2018. This information reflects more confidence of students as they become familiar with earthquake topics and have heard more information about them.

In 2020, 93 % of children knew that during an earthquake, the majority of injuries and

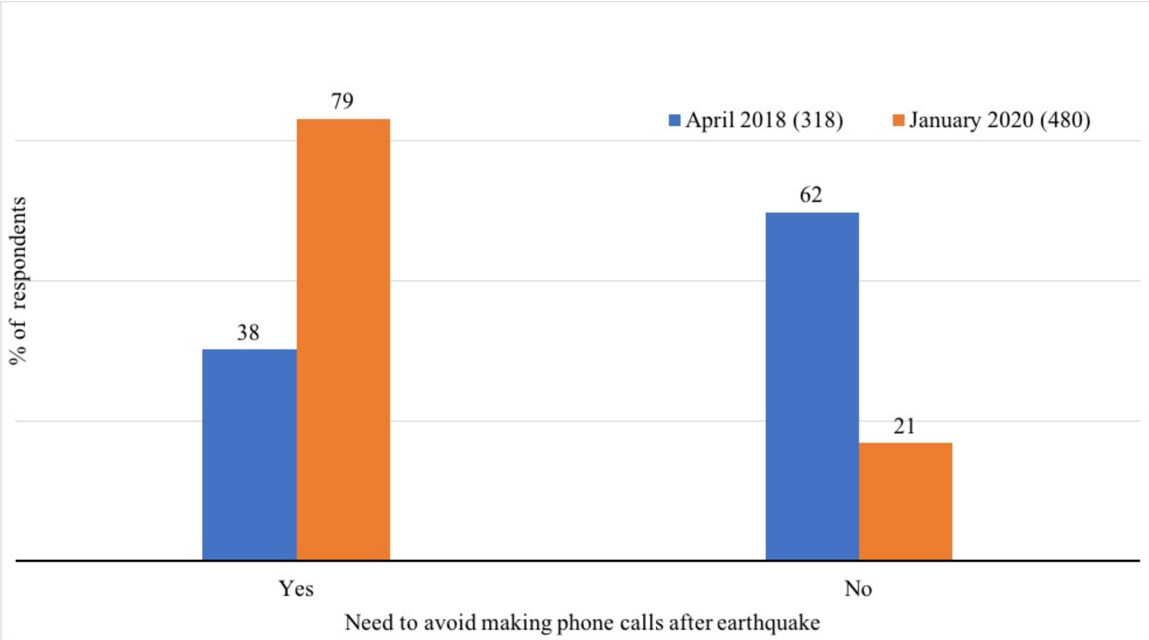


**Figure 5.8:** *Student's knowledge on the recommendation to avoid making phone calls after an earthquake to leave lines available for rescue operations (Q6), before and after the initiation of our education program. ($\chi^2$ = 138.72, p-value = < .00001, the change is significant).*

deaths are caused by people being hit by objects, through the collapse of constructions; the proportion of people not knowing this dropped by 2/3 after the educational program was implemented. More than 2/3 of the students in 2020 were aware about the additional hazards, such as fires, landslides and floods that can be triggered by an earthquake. There is a 7 % decrease for this answer since the 2018 survey, but as students who claimed partial knowledge increased by 7 % as well, a net change in knowledge is not really perceptible on this point.

The proportion of students who regularly discuss earthquake related topics within their families has increased by 18 % (absolute increase; see Table 1). This shows that the education program at schools has led to widespread social learning within communities. This is reinforced by the finding that nearly all students (98 %) are interested in learning more about earthquakes in detail, which will aid communities towards better earthquake preparedness in the long run.

### 5.4.3 Earthquake preparedness and adaptation

In 2018, 36 % of students perceived that to remain alive during an earthquake depends on luck, while this number has decreased by a relative 60 % after our program started and is a concern for only 21 % of students (Fig. 5.9). All possible answers regarding adaptation options to earthquakes record an increase from 2018 to 2020 (Fig. 5.11). The majority

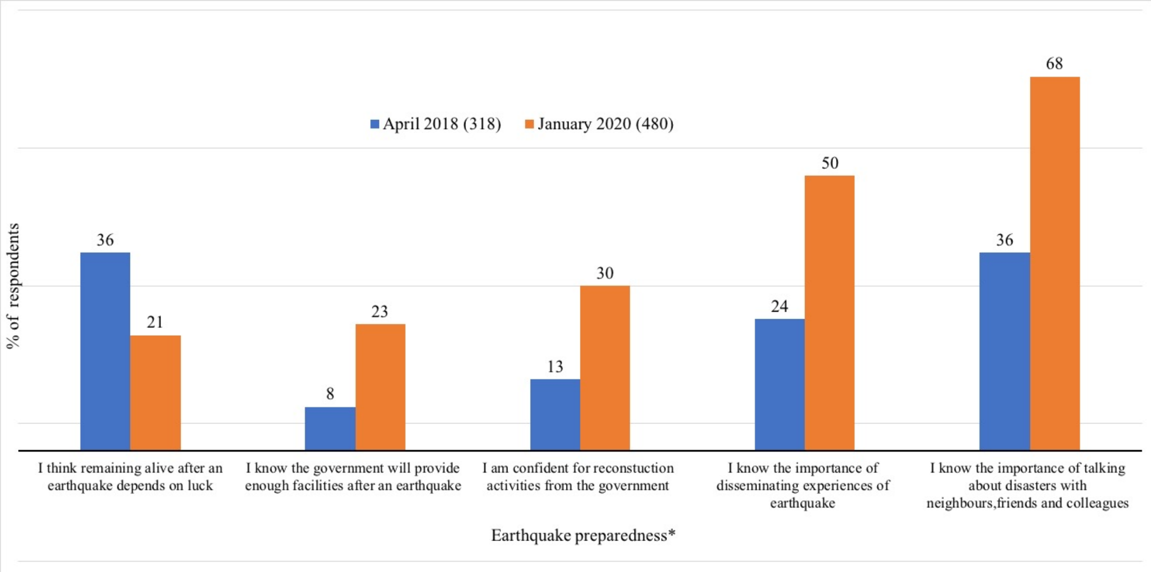


**Figure 5.9:** *Student's own opinion on earthquake preparedness (Q14), before and after the initiation of our education program. *Multiple answers were possible.*

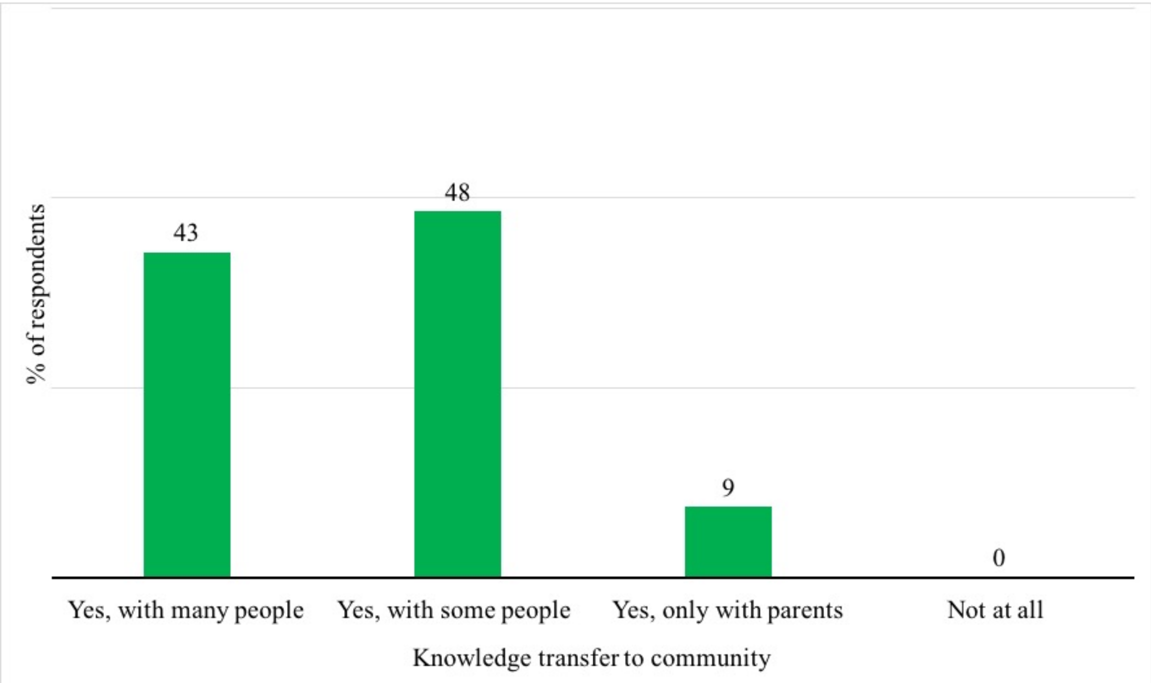


**Figure 5.10:** *Student activities to transfer the knowledge to the community (question e), after initiation of our education program.*

(72 %) of respondents answered that they are aware of the shelter areas and open spaces where they can go in case of an earthquake. The same proportion of people are aware of evacuation areas in 2020, but the increase here is much more important (from 38 to 69 %),

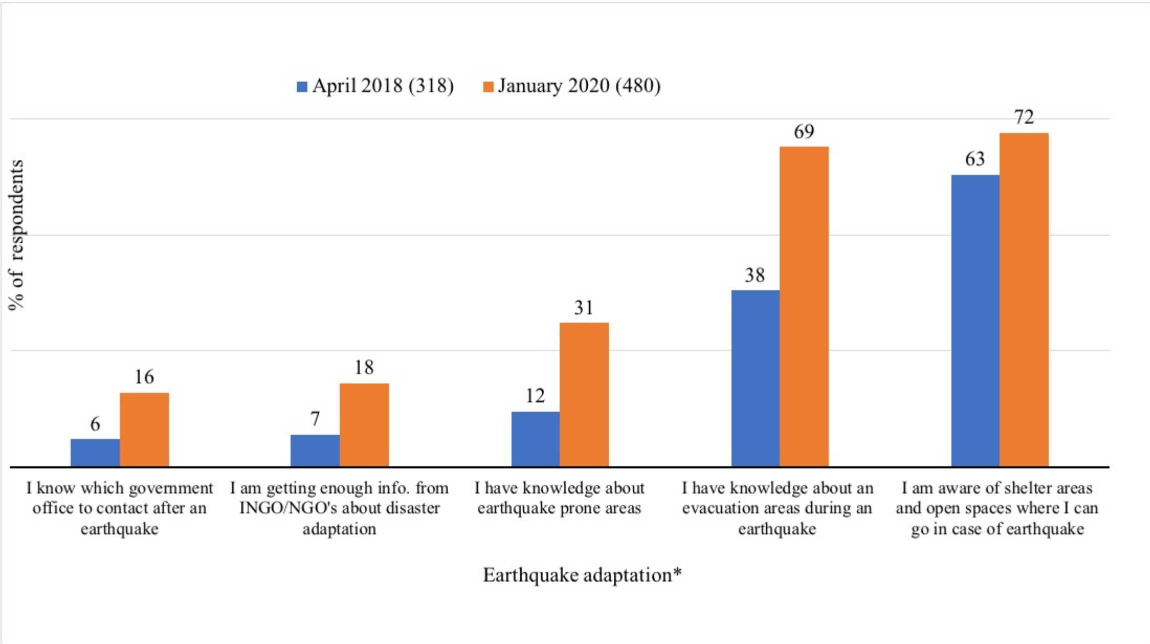


**Figure 5.11:** *Student ideas about earthquake adaptation (Q15), before and after the initiation of our education program. *Multiple answers were possible.*

potentially thanks to the Nepali Emergency Meeting Point signs we installed in schools. The information about which governmental authority to contact after an earthquake is relatively low, but has increased by 10 % (absolute). Information about earthquake prone areas and the reception of knowledge on earthquake disaster adaptation have increased by the factor of 2.5, from 12 % in 2018 to 31 % in 2020 after the education program.

The relatively small number of respondents who claimed that the government will provide help after an earthquake increased by a factor of almost 3: from 8 % in 2018 to 23 % in 2020. This percentage is not yet sufficient in general, but the improvement following our program's implementation is noteworthy. Moreover, the level of confidence in the government's reconstruction activities has also grown, from 13 to 30 %, which is a good sign and shows increasing level of trust. In 2020, 68 % of the respondents knew about the importance of talking about earthquakes with neighbours, friends and colleagues, a nearly two-fold increase in two years. Furthermore, we found that all students discussed their new knowledge and learning about earthquakes with the people around them in the community. Ninety-one percent of the students had talked to at least with some people in the community, only 9 % had discussed this with their parents only, and there is no student who had not had a discussion in her/his surroundings (Fig. 5.10).

### 5.4.4 Perception of risk

More than 60 % of the answers showed that students considered the level of seismic risk in their city as medium, which means their risk perception is underestimated with respect to the actual seismic risk level in the region (Stevens et al., 2018). Only every $6^{th}$ person claims to perceive high risk, which is clearly less frequent than people declaring low risk. As opposed to our expectation, there is very little change in the level of risk perception in the group of students from 2018 to 2020: the medium risk level group is the same, and there is minor change in low and high-risk level groups (Fig. 5.12). This result is a surprise, especially when compared to the 72 % of responses in 2020 who believe that there is more than 70 % chance of experiencing an earthquake larger than the 2015 Gorkha earthquake in their life (Fig. 5.6a).

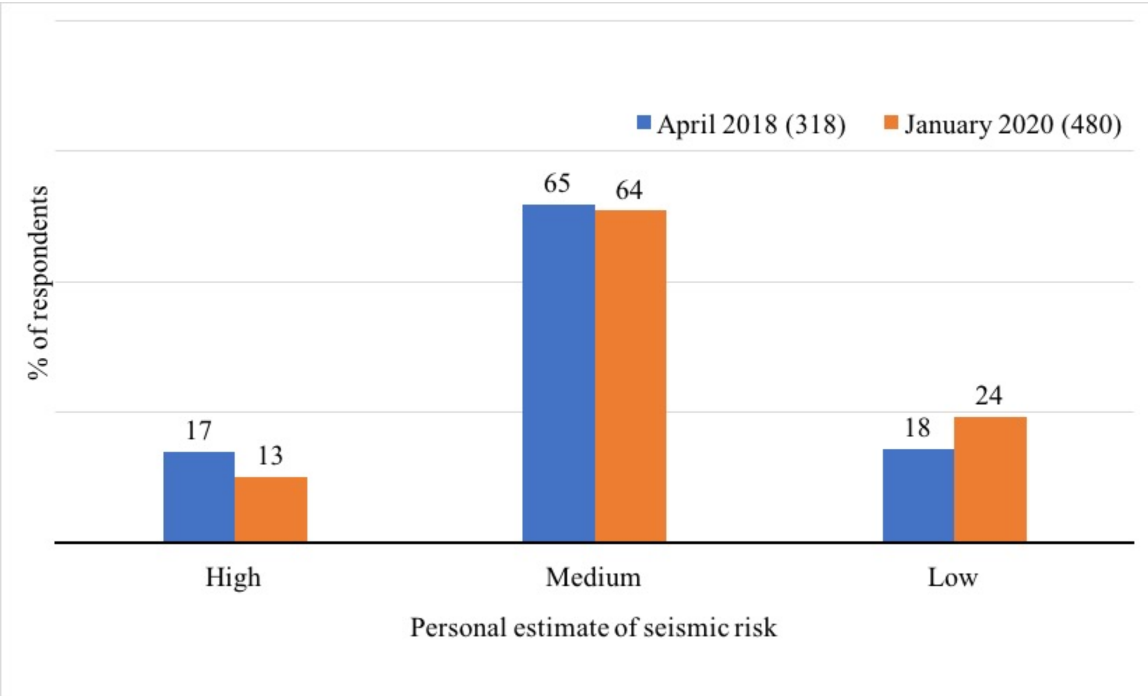


**Figure 5.12:** *Students' perception of the level of seismic risk in their respective location (Q10), before and after the initiation of our education program. ($\chi^2$ = 6.33, p-value = 0.042, the change is slightly above significant level).*

### 5.4.5 Project acceptance and future education

To measure the program's acceptance level, some questions regarding the program itself were also included in the 2020 questionnaire. It is found that 91 % of the students know that a seismometer is installed in their school for earthquake education purposes. A total of 61 % of the students have observed waveforms recorded by the seismometer, either at the school computer (39 %), on the teacher's mobile phone (18 %) or/and on their parents' or own mobile phone (8-8 %). Furthermore, 85 % of the students answered that teachers teach about earthquakes in the classroom regularly (weekly, monthly, on demand, and/or following an earthquake). In 2020, 99 % of the students expressed that they like the earthquake information we have provided them. Regarding future plans, almost all students are very much (69 %) or simply (29 %) interested to learn about earthquakes by inserting the theme in the official curriculum, which can be instituted by the Local, Provincial and Federal Government of Nepal as they have all have some field of possible action. Hence, our program and the methods we use for teaching about earthquakes are well accepted.

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| Q.N. | Question | Answer in 2020 survey | | | Answer in 2018 survey | | |
|---|---|---|---|---|---|---|---|
| | | **Yes (%)** | **Partially (%)** | **No (%)** | **Yes (%)** | **Partially (%)** | **No (%)** |
| Q7 | If a large earthquake occurred at night, could you save yourself? | 65 | – | 35 | 43 | – | 57 |
| Q8 | Do you know that the majority of injuries that occur in earthquakes are caused by people being hit by or stumbling over fallen objects? | 93 | – | 7 | 76 | – | 24 |
| Q9 | Do you know that earthquakes can make additional damage such as fire, landslides and floods? | 68 | 21 | 11 | 75 | 14 | 11 |
| Q11 | The preparedness of a major earthquake is the most important thing. Are you regularly discussing this topic with your family? | 71 | – | 29 | 53 | – | 47 |
| Q12 | Are you interested to know more about earthquakes and its preparedness in details? | 98 | – | 2 | 98 | – | 2 |

**Table 5.1:** *Questions and respective answers about earthquake preparedness among students who participated in the surveys, before and after our education program was initiated in Central Nepal. Respective statistical indicators are reported in Table 5.2.*

| Q.N. | Questions | Observed $\chi^2$ Value | Threshold $\chi^2$ Value | p-value | Remarks |
|---|---|---|---|---|---|
| Q1 | In your opinion, what should be the cause of an earthquake? | 78.15 | 7.81 | <0.00001 | Null hypothesis rejected |
| Q3 | What do you think, how likely is the occurrence of an earthquake in Nepal greater than the magnitude of 2015 Gorkha earthquake in your life? | 43.59 | 9.49 | <0.00001 | Null hypothesis rejected |
| Q4 | What do you think, can your house building resist a large earthquake? | 10.30 | 5.99 | 0.005 | Null hypothesis rejected |
| Q5 | Do all the members of your family know exactly what to do and where to go at the time of an earthquake? | 32.96 | 5.99 | <0.00001 | Null hypothesis rejected |
| Q6 | Do you know you should not call others after an event, to leave the lines available for rescue operations? | 138.72 | 3.84 | <0.00001 | Null hypothesis rejected |
| Q7 | If a large earthquake occurred at night, could you save yourself? | 37.65 | 3.84 | <0.00001 | Null hypothesis rejected |
| Q8 | Do you know that the majority of all injuries that occur in earthquakes are caused by people being hit by or stumbling over fallen objects? | 44.16 | 3.84 | <0.00001 | Null hypothesis rejected |
| Q9 | Do you know that earthquakes can make additional damage such as fire, landslides, floods? | 7.33 | 5.99 | 0.025 | Null hypothesis rejected |
| Q10 | What do you think the level of risk for an earthquake is in your city? | 6.33 | 5.99 | 0.042 | Null hypothesis rejected |
| Q11 | The preparedness for a major earthquake is the most important thing. Are you regularly discussing this topic with your family? | 27.70 | 3.84 | <0.00001 | Null hypothesis accepted |
| Q12 | Are you interested to know more about earthquakes and preparedness in details? | 0.016 | 3.84 | 0.899 | Null hypothesis accepted |

**Table 5.2:** *Summary of questions asked in the 2018 and 2020 surveys, followed by statistical indices of change in 2 years of our program: the corresponding calculated and tabulated chi-square values, and p-values at 0.05 significance level.*

**Statistics**

All questions except the last (Question 12 in Table 5.1, level of interest to learn is 98 % in both surreys) record a clear change in the pattern of answers given following our program's implementation (Table 5.2). The biggest statistical change was seen for Question 6 (avoid post-earthquake use of mobile communications) suggesting a big increase in knowledge and a very new information. Each question (excluding those with multiple choice answers) and their corresponding $\chi^2$ and p values are reported in Table 5.2.

## 5.5 Discussion

### 5.5.1 Have earthquake awareness levels increased?

As a result of the novel school-based education program, themes related to earthquakes are more familiar to the students now than in the past, and their awareness levels have increased since the program was initiated. Students know more about the earthquake phenomena and have changed their behavior to better prepare and adapt to forthcoming earthquakes. Earthquake related knowledge learnt by students at schools has also reached across the broader community, though social learning processes (Reed et al., 2010).

### 5.5.2 Why have the awareness levels increased?

Beyond the prescribed school education, our program has provided an opportunity for informal and free-choice education forms, in which people can learn about topics outside of formal educational settings, which has been well supported by enthusiastic teachers (Falk and Dierking, 2002). This form of social learning enables an increase in knowledge, and through further communication with others, it spreads knowledge in communities, which may lead to changes in attitudes, behavior, and building of trust in society (Reed et al., 2010). This method is widely applied for the study of natural hazards and its management (e.g. Brody, 2003; O'Keefe and Swords, 2010). During our program's implementation, despite being in contact only with the school children, the knowledge has spread much more widely in local communities through social learning, thus reaching and impacting the original and intended target group.

People's behavior can also be developed through education. The idea is that if people are made more knowledgeable about earthquakes, they are more likely to adopt and perform behaviors that will increase their earthquake awareness and preparedness (Hungerford and Volk, 1990). This has similarly been shown for other environmental issues like invasive species, where campaigns building knowledge and awareness changed behaviors therefore reducing risk (e.g. Cole et al., 2019).

As a result of our educational program, earthquake related knowledge has increased and the behavior necessary to cope with earthquakes has also changed. Despite this, the earthquake risk perception of students has not yet greatly changed. Our results show that a realistic

and appropriate distribution of earthquake related knowledge and increased awareness level are not (or not yet) sufficient to influence the perception of risk. Perception is a complex phenomenon and can take a long time to changex (De Dominicis et al., 2015; Estévez et al., 2015; Cole et al., 2019; Shackleton et al., 2019). Education and awareness raising is a key factor for changing long-term risk perceptions – although programs need to be well tailored to appropriate audiences (Lee et al., 2015). Although, some studies discuss the fact that increased knowledge does not always relate to increased risk perceptions, and increasing perceived risk does not necessarily result in the reduction of risk behavior (e.g. Noroozinejad et al., 2013; Petros, 2014). In addition, knowing more of a given topic makes people more certain, self-confident, which may lead to underestimate the related risk (e.g., Stringer et al., 2004). Moreover, increased knowledge and behavior to adapt and to feel more secure during an earthquake should reduce the fear of associated risk and therefore reduce the risk perception. The limited change in risk perception in this study may be due to better knowledge of the hazard and how to mitigate it (Ndugwa Kabwama and Berg-Beckhoff, 2015).
Hence, how people perceive risk is not necessarily related to the actual risk. We cannot draw a definitive conclusion as the related knowledge can contribute to the amplification or the attenuation of the related risk; as such, it could be one of the potential reasons for the low risk perception of people having more knowledge (Reintjes et al., 2016). Risk perception is thus important for preventative actions, but risk perceptions are often biased (Weinstein, 1988). It could be that more time is needed to change students' risk perceptions, and it is also likely that there are other factors such as economic status, gender, age group, location of home in city, etc. that may influence the level of risk perception of people. A repeated survey in the same age category in a few years' time may give more insight into this question. We suggest that further monitoring and adaptation of the education system might be needed to better link awareness raising, behavior change and risk perception change.

### 5.5.3 Further action needed

Since other sources of information, such as newspapers and television, are not easily available to people in the Nepali countryside, we believe that the school is the best platform to transfer knowledge to the community. The proper education at school reaches deep within the families and into the community, and the discussions in those circles are essential to prepare the whole society for future earthquakes. The proportion of students who regularly discuss earthquake related topics within their families has increased by 18 % (absolute increase; see Table 5.1). This shows that the education program at schools has led to widespread social learning within communities, and possibly beyond our program's current area. We therefore, advocate for a continuity of this program and to get education about environmental hazards more deeply embedded in the Nepali education system.

Although this program has increased the earthquake awareness level among students and the broader community in the program area, it is alone not sufficient for seismic risk reduction. Further monitoring and adaptation of the program to promote changes in risk perception and improved learning is advised. Education will help communities to prepare for future earthquakes, but the local, national and regional governments are responsible for the rescue, support and reconstruction operations in the case of a severe earthquake and well as developing and implanting policy to mitigate against threats. People's situation after an earthquake depends on how well they were prepared for the event, so developing policy, for example, on construction quality depending on expected shaking intensities is advised. Since the shaking level of an earthquake cannot be controlled, the impact of an earthquake on the community is strongly dependent on the actions taken by the government for its preparedness, such as education (so far our program's effort) as well as, for example, a suitable, locally calibrated and enforced building code. For both aspects, the provincial governments could undertake some of the efforts drawing on our bottom-up approach, and adapt them to maintain earthquake education in schools, which is an efficient way to make earthquake-safer communities. In parallel, local initiatives are encouraged to strengthen these efforts.

## 5.6 Conclusions

The Seismology at School in Nepal program has been successfully implemented and achieved the aim of raising earthquake awareness and preparedness by educating students in their schools. The program itself and the methods we used for teaching about earthquakes and demonstrations using low-cost seismometers are well accepted by students and teachers. The new knowledge learned by the students at school reaches their parents and is transferred into the local community. The results we observed through two surveys, before and after initiation of the education program, are measurable, statistically significant and with positive changes for earthquake related knowledge and preparedness level, but not (yet) for the perception of the related risk. A high and positive impact of the program on the students and their communities is encouraging for the continuation and expansion of the program in the region. Governmental institutions are encouraged to build on this experience as well as develop further policy to mitigate the risk of future earthquakes in Nepal.

## 5.7 Acknowledgement

We greatly acknowledge students, school teachers and principals from the school participating in the program. We are very thankful to people who helped carrying out the surveys. We highly appreciate the American Geophysical Union for their AGU-Celebrate-100 grant support which allowed to invite Nepali teachers to the workshop. We greatly acknowledge the Institute of Earth Sciences and the Faculty of Geosciences and Environment at the University of Lausanne for hosting Shiba Subedi as a doctoral student, and for their support for instrumentation. The funding from Federal Commission for Scholarships for Foreign Students, Switzerland, for Shiba Subedi's PhD thesis is well acknowledged. We warmly thank Anne Sauron, Peter Loader and Paul Denton for valuable suggestions and useful discussions. We are also thankful to Mrs. Apsara Pokhrel for translation and typesetting of the survey questionnaire in Nepali language.

# Chapter 6

# Conclusions and perspectives

## 6.1 Conclusions of this thesis

The history shows that tens of thousands of people have died in Nepal from earthquakes, while the Mw 7.8 Gorkha earthquake in 2015 alone killed about 9'000 and caused damage equivalent to 50 % of the national gross domestic product, a loss that is underestimated according to the scientific community. People's awareness and their behavior during an earthquake can play a key role in trimming the risk of associated natural hazards, but earthquake-related classes are missing in the Nepali education system, and consequently the related knowledge in the society is insignificant. As Nepal lies in a region where the seismic risk is very high, education to make people aware of an earthquake and its forethought is of maximal importance. Moreover, teaching students in school could be the best idea to introduce knowledge to the local communities. I have followed this concept in Nepal in a region where people nearly never get a chance to learn about earthquakes. Our program has been successfully implemented to achieve the aim of raising earthquake awareness and preparedness by educating students in their classes. This thesis concludes the findings in two parts.

For the educational relevance of this project (Chapter 5 and educational implementation of Chapter 4), we applied different activities in participating schools in western Nepal. Various educational efforts involving students, teachers, and communities in earthquake education, and primarily a workshop for teachers, allowed them to gain knowledge of earthquakes and to enhance its anticipation in better ways. The program itself and the methods we used for teaching about earthquakes demonstrated with low-cost seismometers are well accepted. The new knowledge learned by the students at school reaches their parents and is transferred to the local communities. The results we observed to examine the impact of the program for earthquake education are measurable, statistically significant with positive changes for earthquake-related knowledge and preparedness level, but not (yet) for the perception of the related risk, which may require more time. The high concern and positive impact of the program on the students and their communities are encouraging for the continuation and expansion of the program in the region. Hence, the project has started to help this region of Nepal to prepare for future earthquakes, and we hope that the initiative is spread to other regions of the country as well. Open data via Raspberry Shake server and freely available educational resources through our program's website could help to extend education and outreach activities in many other schools in the region and to start such activities in the remaining part of the country.

The second aspect of this thesis describes the seismological results using the seismic data acquisition by the Nepal Schools Seismic Network. These data are used in the seismological implementations like local earthquake records, corresponding shake map plots, and event detection capability of the network. Furthermore, data are used to calibrate a new local magnitude equation for Nepal which is applicable to consistently compute the magnitude of local events (Chapter 4). Also, the detection and location of local earthquakes could be done with the data. Hence, low-cost solutions are suitable for densifying the networks designed for studies of local and regional events in parallel with educating non-scientist communities. Such low-cost networks remain important to advance the forefront of scientific investigation and continue to provide new structural and seismological perspectives (Chapter 2). In the same time, more effort should be put on reaching out to the society. Therefore, our program has established a connection between the scientific community and the local population.

The subsequent two sections discuss further ideas for the educational and seismological development, to continue the work in this thesis.

## 6.2 Educational perspectives

In our program, we have so far focused on educational activities in the schools, as existing structures to transfer information to students. These efforts can continue in a number of ways, but two-way communication with the society can also take other forms, as described in the sub-sections below.

### 6.2.1 At schools

#### 6.2.1.1 Earthquake evacuation drills

During and after an earthquake, life-protecting actions must be taken immediately at the first indication of the tremor. Earthquake evacuation drills are an extremely important part of preparedness as they teach how to respond to the complications of an actual earthquake. The key message of earthquake evacuation drills is to teach and make people practice WHERE to seek shelter and HOW to protect their heads and bodies from moving objects. During the drill practice in schools, dropping, covering, and holding actions can be taught in the classrooms until the shaking is over (Fig. 6.1). After that, the teacher leads the students out of the building and calls the roll to make sure everybody is there and safe. If a quake hits when the children are in the playground, the teacher asks them to gather in an open space away from the school building, at the emergency meeting point (available at our website download page).

The concept of earthquake evacuation drills has been already applied in some countries and the aim of the improvement on risk reduction and better response for the preparedness has been validated. For example, in Japan, school earthquake drills are regularly conducted (Morita et al., 2016), and this concept has been applied for community-based earthquake drills in California (Simpson, 2002).

**Figure 6.1:** *School children in Japan practicing an earthquake drill. (Photo: AFP).*

We aim to prepare guidelines adapted to the Nepali education system and infrastructure and upload them on our webpage, which later could be used for drills in schools. The benefit of keeping information and guidelines online is that any of the schools across the country, even if they do not participate in our program, can follow the idea and introduce drills in their places. Since the impact of earthquake evacuation drills would only be visible if the practice is regular, we propose to perform earthquake evacuation drills in participating schools once a month. In secondary schools with 13-16-year-old students the class teachers can lead these drills, and for basic level students of the 6-12-year age group a group of teachers can implement this training. At the same time, principals can evaluate the performances of teachers and students and later give feedback to respective teachers to improve what is needed. These efforts will provide opportunities for students to learn and practice the rhythm of protection in case of a real earthquake and to build confidence in such exercises.

#### 6.2.1.2 Regular communication with teachers via social media

Social media are primarily internet-based, well-known communication tools, not only to share own opinions and entertainment but also to share valuable information. These media may make learning easier and can be used in different ways for educational purposes. Public networks such as facebook, twitter, blogs, etc. play an increasingly important role during and in the aftermath of natural disasters as they can be used to provide details on infrastructure conditions, disaster response, and reconnaissance purposes. The information gathered via such media are important for emergency response of natural disasters such as floods (Kim and Hastak, 2018), hurricanes (Lachlan et al., 2014), and of course earthquakes (Gao et al., 2011; Kaigo, 2012; Kryvasheyeu et al., 2016).

In Nepal, until and unless people don't experience shaking, most of them get information about the seismic activity mainly via social media. Facebook, youtube, twitter, and others are becoming more and more familiar to local people in Nepal nowadays. They see social networks can be the perfect platform to exchange information with many people at the same time. For our educational seismology program, instead of making calls to each and every responsible individual at schools, we can post respective information on social media where it reaches the targeted groups very easily and on time. One can use social media after natural hazard events to share the conditions with their family and friends, and also to raise funds for relief efforts.
The usage of social media is beneficial for us also to see how people evaluate our efforts for awareness and preparedness. When people experience an earthquake and the official NSC announcement is due, many people contact us for information that we cannot announce, but we can at least say how far the earthquake is from their region by looking at the waveforms at local seismometers. We have noticed that people feel proud and excited to share earthquake related information on their facebook profile.

#### 6.2.1.3 Training for teachers

The operation of the installed seismometers in schools for teaching and sometimes for minor repair requires the active involvement of trained teachers in each school. The initial training in the form of the two-day workshop was very useful and successful, nevertheless, to further train them, to develop from basic to advanced level, we aim to continue such activities. The training could be in two ways: either in an actual workshop for example once a year, or through online video conferences every six months. These trainings are also meant to keep the teachers' involvement in the project. Furthermore, we can also advise or help teachers during our visits to the schools, and address their concerns or technical issues.

The reduction of environmental noise (Fig. 3.14), fresher air, increased visibility, clearer water, and liberated wildlife are positive effects that appear around the world due to the implemented lockdowns to contain the spread of the COVID-19 pandemic. Along with these effects, people's behavior has also been changed with the lockdown. In Nepal, schools and teachers have started to adapt technology to conduct educational activities from home through online meetings, online discussions, and video conferences during the lockdown period. As they are already familiar with these online tools, implementing teacher's training and even open sessions for students with experts answering their questions now seems more conceivable. In addition, pre-defined schedules create a possibility for other interested persons from the community to join. This would help to remain connected with teachers and students until the next visit. In case our program develops more physical presence in Nepal (i.e. with staff), it is also possible to organize separate meetings for a particular school on their request.

#### 6.2.1.4 National earthquake safety day and memorial day of Gorkha earthquake

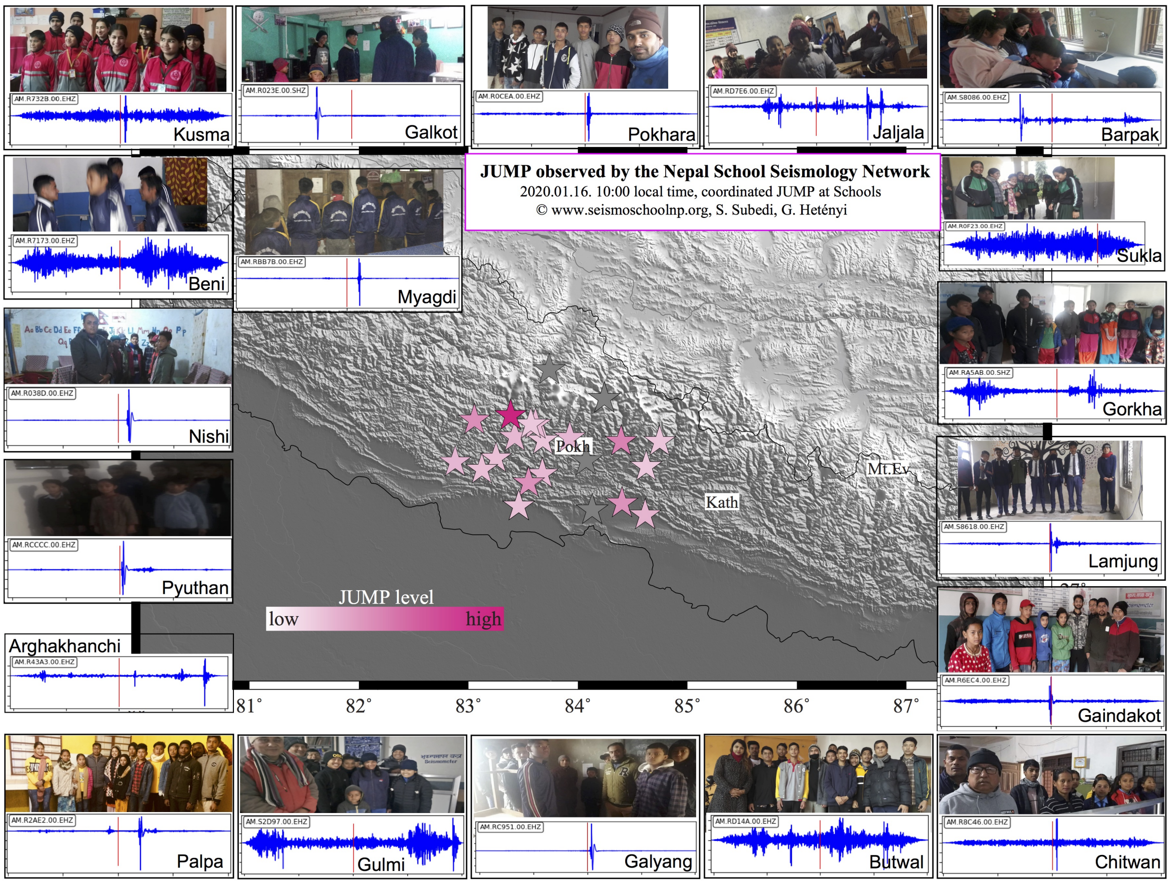


**Figure 6.2:** *Coordinated jump at 10 am local time on the occasion of the 22$^{nd}$ National Earthquake Safety Day on Magh 2 of the Nepali calendar (16 January 2020) organized by our project and observed by the Nepal School Seismology Network.*

There is a special day for the celebration in memory of earthquakes from the government level. On the basis of the geographical and historical data on earthquakes, a mega-earthquake of Mw 8.2 had hit eastern Nepal on 15th January 1934 (Nepali calendar B.S. 1990 Magh 2). The day was then marked as National Earthquake Safety Day starting from 1999 to spread awareness about earthquake safety methods. On this day, events and rallies are organized on national, local, and community levels, and our program also plans to undertake some activities in schools related to earthquake awareness and its preparation on that day. This year (in 2020), on the occasion of the 22$^{nd}$ National Earthquake Safety Day, we organized a coordinated 'jump near your seismometer' action to celebrate this day and distributed a poster on the student's involvement and the outcomes (Fig. 6.2). Future plans could include earthquake awareness campaign in the countryside, earthquake related essay writing competition, quizzes on earthquakes, classes on earthquakes for local people by students, and other creative ideas.

Another occasion follows from the most recent major earthquake in Nepal: the 2015 Gorkha earthquake occurred on Saturday (Nepali calendar Baisakh 12), and it is somehow considered to have been lucky for Nepal having been hit on Saturday, the only holiday of the week, at 11:56 local time, when most people were outside. It is estimated that the death toll would have been much higher if the disaster had struck on any other day during the week. It would have been difficult to save children trapped inside the 5'500 school buildings that were destroyed in the 2015 earthquake. To celebrate the Gorkha earthquake Memorial Day, sharing personal experiences of the earthquake and analyzing what people did during the crisis could be a start. Such measures would help students to gain a new level of confidence by further participating in discussing these topics, and sharing them with their environment.

#### 6.2.1.5 Earthquakes and Hindu religion

The explanation for the cause of an earthquake in the Nepali community is strongly based on its description in the Hindu literature. These beliefs are ancient and rather strong, as the scientific frame is rarely explained and most people follow religious rules very seriously in their daily lives. To make a better understood link between science and religion in this context, and also for better mutual understanding of the respective ideas, we need to know what and how the Hindu literature says about earthquakes.

According to many scholars, the oldest religion in the world is believed to be Hinduism with its roots and customs dating back to about 5'000 years. Hinduism, currently the third-largest religion after Christianity and Islam, has originated in the Indian subcontinent and currently counts about 1.1 billion followers, including about 80 % of the population in India and Nepal. The fundamental principle of this religion is based on the idea that people's actions and thoughts directly determine their current lifestyle, future conditions throughout their life in this world and after their death. People who respect and follow Hinduism also consider natural entities as Gods.

Since modern seismology has not reached to the majority of people in Nepal (and probably other countries in the region either) who strongly believe in religious explanations, there are many stories in the local Nepalese communities regarding what causes an earthquake, who is responsible for the creation and destruction of the Earth, and similar themes. We believe that along with the scientific interpretation of earthquake processes, it is interesting to examine why people following Hinduism have so strong religious views, how Hindu literature explains about earthquakes, and what are the possible links with scientific explanations. Therefore, we realized that it is a good attempt to consolidate ideas regarding the description of earthquakes in Hinduism by compiling information documented in different sources. I have started this work, including the identification of some related illustrations, and plan to finalize it in the coming months to then make the synthesis available to the Nepali community.

#### 6.2.1.6 Article in national newspapers

During our fieldworks, we observed that most of the 1st generation people in metropolitan areas read printed newspapers and second generation adults read both printed copies and online materials. Hence, beyond online presence, newspapers should ideally touch more on earthquake-related topics than currently. This would be a clear extension of our activities outside the schools, both at the regional and national level.

I propose to describe the phenomena of earthquakes and related questions including simple illustrated figures that can help people better understand these. A document compiling such articles could be subsequently made available to schools and community libraries.
Our program has already started to be involved in writing newspaper articles on earthquake-related topics, and some of these are published in the most popular daily newspapers such as Kantipur, The Rising Nepal, and Republica National Daily. These articles are listed on the media mentions page of our project website (http://seismoschoolnp.org/?page_id=746).

### 6.2.2 Crowdsourcing

Beyond targeted work with schools, science can learn a lot from contributions from society. Citizen's inputs are very important and were the only source of information to know what happened during a historical earthquake or volcanic eruption. Similarly, the contributions of citizens today are helpful for seismologists to study recent earthquakes and their behaviors (Liang et al., 2019; Quitoriano and Wald, 2020; Diaz et al., 2020). Experience shows that such approaches can work at the global scale to produce reliable and rapid results on earthquake location from crowdsourced data (Steed et al., 2019). World's earthquake monitoring agencies have been using citizen's information to make event announcements faster and to assess the intensity of respective shaking. For example, the European-Mediterranean Seismological Centre has been developing systems for the detection of felt earthquakes via its websites (http://www.emsc-csem.org, m.emsc.eu), its LastQuake smartphone app, and twitter.

In Nepal, currently the NSC is collecting 'Did you Feel it' reports after every $M \geq 4$ earthquake, but very few people fill out such reports (source: Lok Bijaya Adhikari, pers. comm.) personal communication). In our program, we strongly encourage students, teachers and local people to fill out NSC forms, and we teach citizens how to compile their observations in such reports. In parallel, we inspire people to post shaking information and their observations on social media even if the quake doesn't get published in the national catalogue. There is another way to submit such information via the EQInfo smartphone application developed by Gempa, which is the application currently used by students and teachers to see the real-time waveforms recorded by seismometers. Also, we suggest buying a personal

RS1D seismometer to those people who are wealthy enough and interested in doing so. This approach has great value for the emergency response in case of moderate and major earthquakes.

### 6.2.3 Earthquake awareness song

The use of audiovisual media is one of the most powerful ways to raise awareness. This is the approach where people entertain, educate and inspire each other around a topic together at the same time. The main genres of Nepali music include folk, classical and western, where folk music is one of the most popular type of music because of its characteristics as: simple to understand, easy to sing and to follow, and not-limited to a particular region and to any age group. The audiovisual products reach dispersed communities ranging from large TV audiences to smaller smartphone user groups in developing countries (Cidota et al., 2016). The visual tools can be much more successful than oral or written channels in explaining the basic science working with earthquakes among vulnerable communities where illiteracy is significant and there isn't much awareness. The reason behind this is that video can be presented in a simple, yet convincing way. Since the literacy rate in Nepal strongly depends on the age group, and it is less than 50 % for people aged over 40 years (Dhakal, 2018), the audiovisual document is the most suitable way of communication for the older generation, too.

There are some successful examples where audiovisual documents had great impact for the related awareness in Nepal. International NGOs running in Nepal such as UNICEF, UNDP and UN are following the audiovisual idea to spread the message and awareness to the targeted people (see example here https://www.youtube.com/watch?v=skDBOSOvwzI).

With these motivations, first I wrote the lyrics of a new, dedicated song for earthquake awareness and anticipation, in Nepali language. For the writing style, I used my 10 years' experience in the Nepali music field where I have composed lyrics and music for more than 20 songs which have been viewed by millions of people. Then, I asked a singer to compose the melody and also to sing the song, and finally, with the visualization, the audio-video piece is completed. This is the first audio-video document to spread a message for earthquake awareness and preparation to the entire community and all age groups. The document is called, "Earthquake awareness song", and explains how to prepare to survive an earthquake along with description of earthquake causes and related consequences in a simple text, regarding the frequent concerns of citizens like the actions that people should take before, during and after an earthquake for its better anticipation. The earthquake awareness song text in Nepali is presented below, with the best English translation for content (and not to make a good English song). The final audiovisual document is being finalized (with some delay due to COVID-19) and will be available soon online at YouTube.

## Earthquake awareness song भूकम्प सचेतना गीत

नब्बे सालको भुकम्पले दसौं हजार मार्यो
दुइ हजार बहत्तरमा फेरी उस्तै पार्यो ।
के गरेमा बाचिन्छ के के गर्न हुन्न
केहि कुरा बताउछु पर्यो हजुर सुन्न ।।
क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।

An earthquake in 1934 (1990 B.S.) killed about ten-thousand people,
In 2015 (2072 B.S.), the same thing happened again.
What should we do to survive, and what we should not do,
What should we do to survive, and what should we not do?
I will tell you something, so listen:
Just as you learn A-B-C, everyone learn how to prepare to survive an earthquake.

आज सम्म बिज्ञानले पत्ता लाको छैन
कैले आउछ कत्रो आउछ भन्न सकिदैन ।
कहाँ आउछ भुकम्प आउने कारण के हो
धर्ति मुनि चट्टान सर्दा जमिन हल्लिने हो ।।
क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।

To date, science has not found out,
It cannot say when and how big it will be,
Where an earthquake will happen, and what is the reason?
Plate tectonics (moving rocks beneath the earth) is the cause of earthquakes (shaking of the ground).
Just as you learn A-B-C, everyone learn how to prepare to survive an earthquake.

पहिलो कुरा भुकम्पले मान्छे मार्नी हैन
तर हाम्रो घर भत्किए हामी बाचिदैन ।
घर बलियो बनाम अब जग दरिलो खनम
आफुले बनाम पहिला अरुलाई नि भनम ।।
क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।

The first thing: earthquakes themselves do not kill people,
But if our houses collapse, we will not survive.
Build stronger homes, prepare stronger foundations,
Build first yourself and then tell others
Just as you learn A-B-C, everyone learns how to prepare to survive an earthquake.

**जब भयो राति अनि बल्ल बुडी ताती**
**त्यसै गरे भुकम्पमा बाचिदैन साथि ।**
**आइहालेमा भुकम्प के गर्ने कहाँ जानी**
**परिवारमा छलफल गर्नु अति राम्रो बानी ।।**
**क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।**

Most people do business at the very last minute. ("When night came, finally it was hot.")
If we behave the same way with an earthquake, we will not survive.
What to do, where to go in case of an earthquake,
Discussing within the family is a very useful habit.
Just as you learn A-B-C, everyone learns how to prepare to survive an earthquake.

**हल्लिहाल्यो घर भने डराउन हुन्न**
**प्रकृतिलाइ सकिदैन रोक्न अनि थुन्न ।**
**टेबलमुनि ढोकामुनि बस्नु घर भित्रका**
**खुल्ला ठाउमा गैहाल्नु भवन बाहिर भाका ।।**
**क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।**

When your house starts shaking, do not be scared,
Nature cannot be stopped or controlled,
If you are inside buildings: hide under the table, or at the door,
If you are outside: go immediately to an open space.
Just as you learn A-B-C, everyone learns how to prepare to survive an earthquake.

**कोइ कसैको घर भत्के नभएमा बास**
**खुल्ला ठाउँ काम लाग्छन नभत्काउ न मास ।**
**क्षती धेरै हुन्छ हजुर लोभी धेरै भए**
**केलाई चाहियो सम्पती जीवन नै नरहे ।।**
**क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।**

If someone's home collapses, and there is no place to stay,
Open spaces are useful, so keep these places free, don't fill them,
Damage will be high if we behave greedily,
If we don't survive, what is our wealth worth anyway?
Just as you learn A-B-C, everyone learns how to prepare to survive an earthquake.

मैले जे जे भने यहाँ भोग्ने हजुरले हो
अर्को ठुलो भुइचालोमा सबै जोगिने हो ।
स्कुलमा नि यो बारेमा सिकाइदिनुस गुरु
भोलि पर्सि न पर्खिउ आजै गरौ सुरु ।।
क ख ग ए बि सी सिके जसरी, सबैले सिक है भुकम्पबाट बच्नी कसरी ।।।

This is MY message, but YOU are facing the reality.
We all hope to survive the next big earthquake.
Teachers in schools: teach about this as well.
Don’t wait for tomorrow, make a start today.
Just as you learn A-B-C, everyone learns how to prepare to survive an earthquake.

Lyrics: Shiba Subedi
Music/Vocal: Pashupati Sharma
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## 6.3 Seismological perspectives

In Chapter 4, we discussed about the seismological implementation of the project including a new local magnitude equation calibrated based on the data observed by the Nepal School Seismology Network (NSSN). The seismometers that we installed for the NSSN are Raspberry Shake 1D (RS1D), a single (vertical) component geophone with 0.7 - 29 Hz flat frequency response. The main limitation of using the NSSN data for seismological studies arises from the sensor itself. Considering these, there are still some seismological studies that could be carried out. In this section, different seismological perspectives are described briefly.

### 6.3.1 Earthquake detection and location

An earthquake is usually located by the match or misfit between observed arrival times of seismic phases at seismic stations, and predictions of these arrival times for different source locations using a given velocity model, which is considered to be a representation of the true velocity structure. The traditional manual detection of earthquakes by looking P and S wave on the waveforms is possible with the NSSN, but the large volume of data from 22 seismic stations can increase processing times significantly, which makes it a very time-consuming effort and therefore – lacking a dedicated analyst – we don’t prioritize this approach. To detect local earthquakes in an automated way, a good alternative that is most likely to be carried out is a so-called friendly earthquake detector, the Lassie program (Heimann, 2016;

López-Comino et al., 2018). Lassie is a stack-and-delay-based coherence detector which finds and locates events using continuous data from a temporary seismic network. The program gives positive detection when the network stacked cross-correlation sum exceeds the defined threshold of median absolute deviation. The choice of detection threshold influences the detection performance, where a low threshold enables the detection of small events, but it does at the price of a higher number of false detections. The Lassie program can be used for the detection of events and to provide approximate locations at the same time. Given that Lassie is principally based on the characteristics function of amplitude envelopes, it will give positive detection not only for earthquakes, but also for coherent human-made noise in multiple stations (Fig. 6.3).

The most widely used approach for earthquake detection is the traditional Short-Term Average/Long-Term Average (STA/LTA) trigger method (Withers et al., 1998). We also propose to use an STA/LTA automatic trigger method for earthquake detection (Fig. 6.4). This algorithm calculates the average values of the absolute amplitude of a seismic signal in two consecutive moving-time windows, STA and LTA, and then the STA/LTA ratio. The STA is sensitive to seismic events whereas the LTA provides information about the temporal amplitude of seismic noise at the site. The detection is considered to be triggered if the STA/LTA ratio exceeds the given threshold value. Successful detection of seismic events depends on the proper settings of the trigger parameters, which have to be selected based on the network preferences. The STA and LTA time window lengths, the STA/LTA threshold level, and the STA/LTA de-trigger threshold level are important parameters that need to be chosen before using the algorithm for event detection.

Since a simple STA/LTA trigger can be applied for a single station, the advanced form of STA/LTA can be implemented for network data, and is called a coincidence trigger. In this approach, single station trigger results are compiled to assess the level of overlap, and the coincidence trigger value can be computed as the sum of the stations where the detected trigger exceeds the given threshold value.
Very first results using the Lassie program to detect and locate earthquakes are presented in Figure 6.5. Since Lassie uses the stacked cross-correlation sum value as threshold, a threshold of 140 has been set. In case of correct detection, the detection value has observed 310 (quite higher than threshold value) and the detection value is just above the threshold value in case of false detection. For the further detection, we will play with theses parameters a bit. Some solutions are located close to the respective NSC location, but some of them are far from these. Further adjustments with Lassie are work in progress. In parallel, I inquired about other programs for earthquake location and I'll openly think and look around for all possible solutions that can apply for earthquake detection and location with NSSN data.

To locate earthquakes more accurately, I will try two approaches that have been applied broadly in the earthquake location domain: (1) the Non-Linear Location algorithm (Lomax et al., 2000) and (2) HypoDD (Waldhauser, 2001), where NonLinLoc is an absolute earthquake

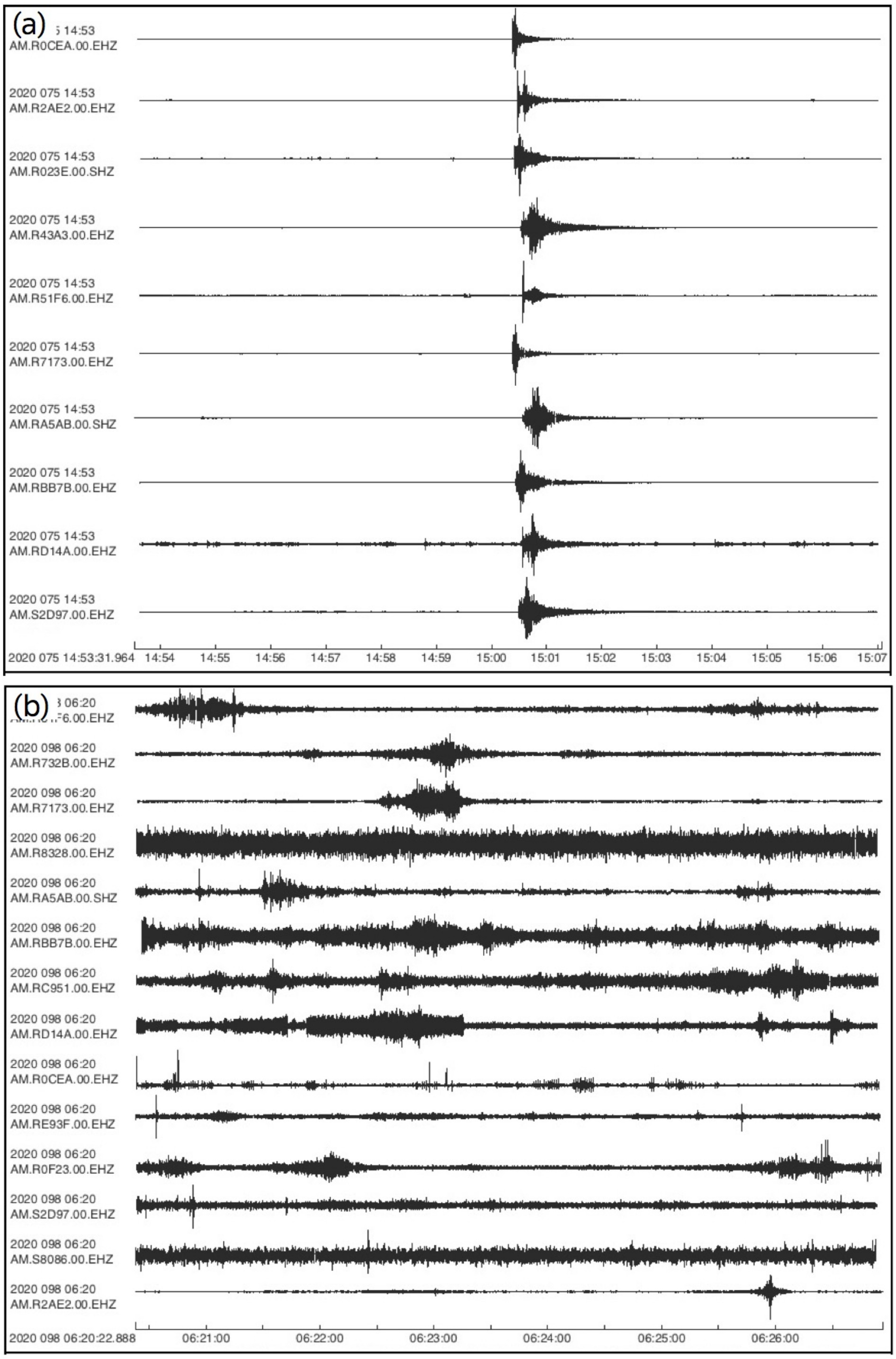


**Figure 6.3:** *Earthquake detection examples using Lassie program. (a) Correct detection, found detection value 310. The event is also published in the NSC catalogue as a* $M_L 5.0$ *earthquake. (b) False detection, the detection value (141) is just above the threshold value. The threshold value is the network stacked cross-correlation sum and has been set to 140 in both cases.*

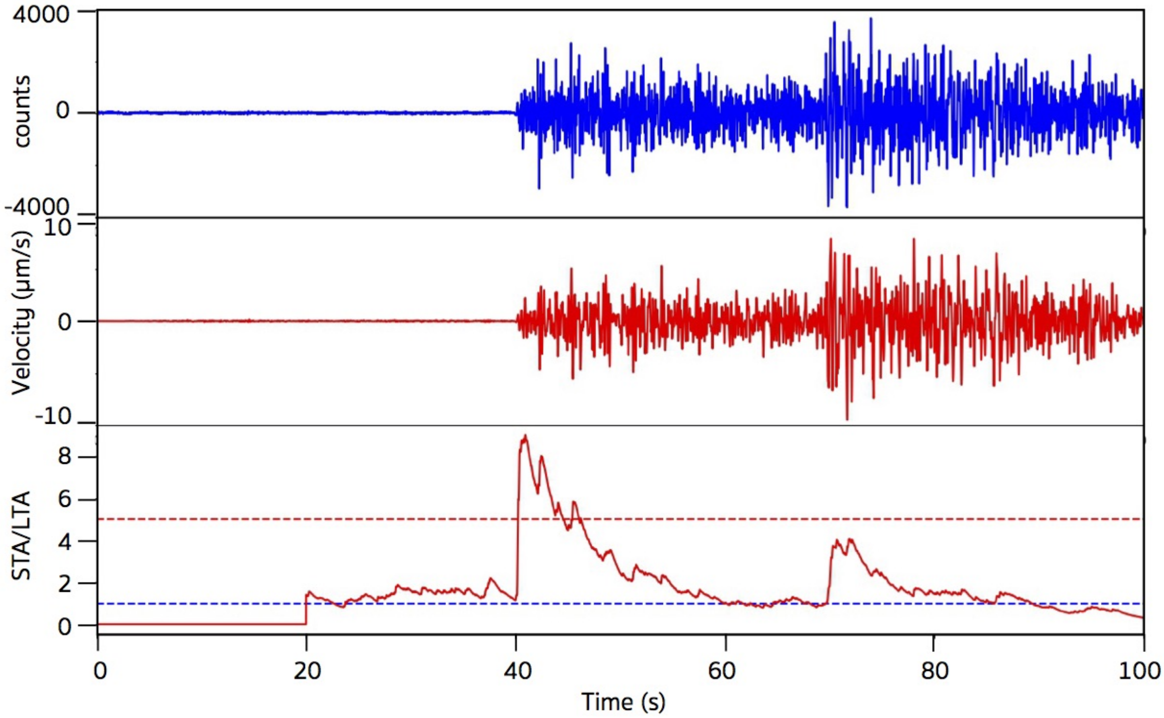


**Figure 6.4:** *Example of STA/LTA trigger detection for an $M_L$ 4.2 earthquake recorded by a NSSN station. Top: raw seismogram. Middle: seismogram filtered between 0.7 and 7.0 Hz. Bottom: the value of STA/LTA with time window lengths of 2 and 20 s, respectively. The red and blue dashed lines are for the on-threshold and off-threshold values (5 & 1), respectively.*

location algorithm while HypoDD is a relative earthquake location. The suitable velocity model needed to apply these earthquake location routines is already available: a local velocity model for Nepal based on quarry blasts (Pandey et al., 1995), which is used by the NSC, and also in the example using Lassie shown in Figure 6.5.

In general, seismic network design is based on the purposes of the study, which in our case was dual: educational and observational. The NSSN is suitable to study the seismicity in the area as long as the stations are installed with ca. 20 - 30 km average inter-station distance. Currently, the 22 stations cover an area of about 200 km east-west and about 100 km north-south. With this, we can reasonably aim to locate events inside the network, with primary azimuthal gap < 180°, events close to the seismic stations (< 100 km). The NSC publishes event information openly when an $M_L \geq 4$ earthquake hits inside the territory of the country. The NSSN station coverage is locally denser, therefore we intend to reduce the location uncertainties and possibly to detect more and lower magnitude events that occur within our network.

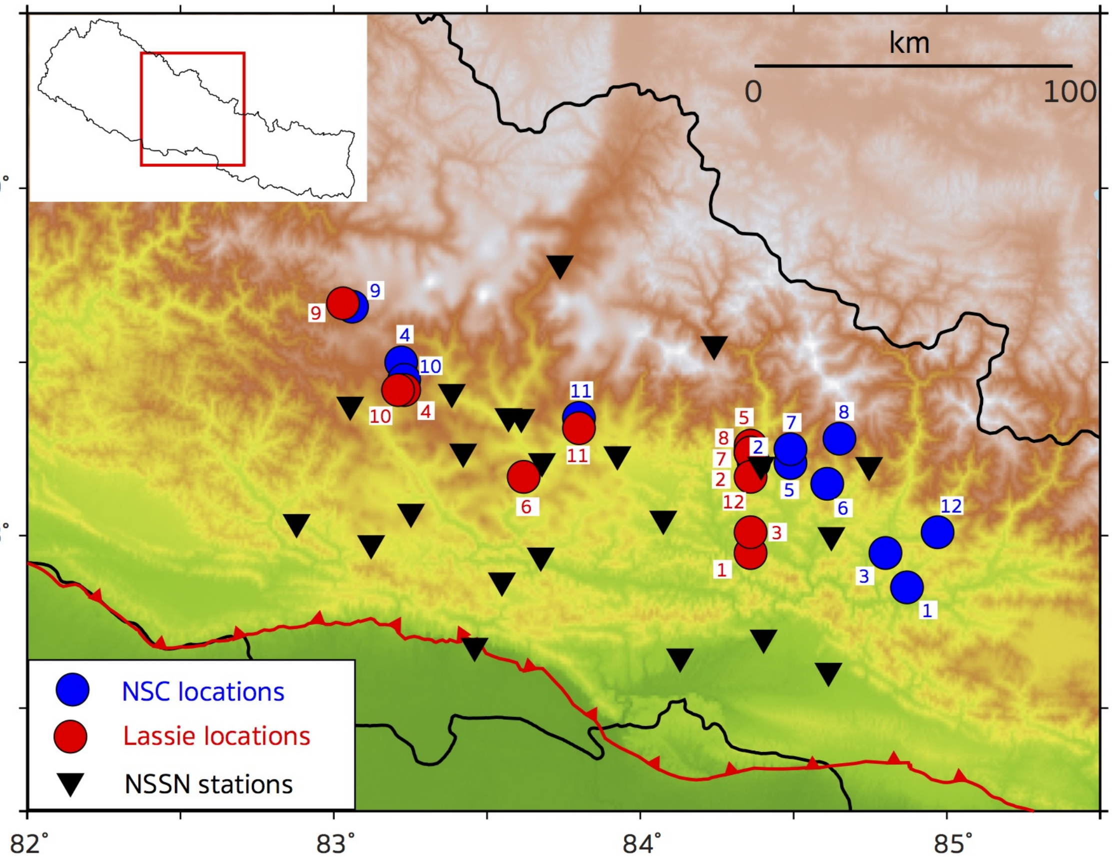


**Figure 6.5:** *Earthquake location example using the Lassie package. Blue circles are NSC locations, red circles are Lassie locations using NSSN station data (black triangles) only. ID numbers refer to the same earthquakes. Some earthquakes solutions with Lassie are located close to the NSC locations (e.g., labels 2, 4, 9, 10, 11), others are located farther from the NSC locations. Red fault line is the MFT, black line is the national boundary.*

### 6.3.2 Template matching

In classical earthquake detection many small events are missed as they are not clearly distinguishable from noise. A solution detects these is a similarity-based earthquake detection technique called template matching, which has been widely used in seismology for the detection of tectonic tremor and small earthquakes. This approach correlates pre-defined templates, usually from already detected events, with continuous recordings to detect events that are similar to the templates (Gibbons and Ringdal, 2006). This method can be applied with tens of seismometers installed at a few to tens of kilometers inter-station spacing to achieve a sometimes significant increase in the number of earthquake detections (Shelly et al., 2007). Recent studies have shown that the application of template matching can potentially detect earthquakes substantially below the noise level (Li and Zhan, 2018). The underlying idea of template matching approach is that0. nearby earthquakes that likely happened on the same fault have highly similar waveforms. An example of a seismic swarm in Valais,

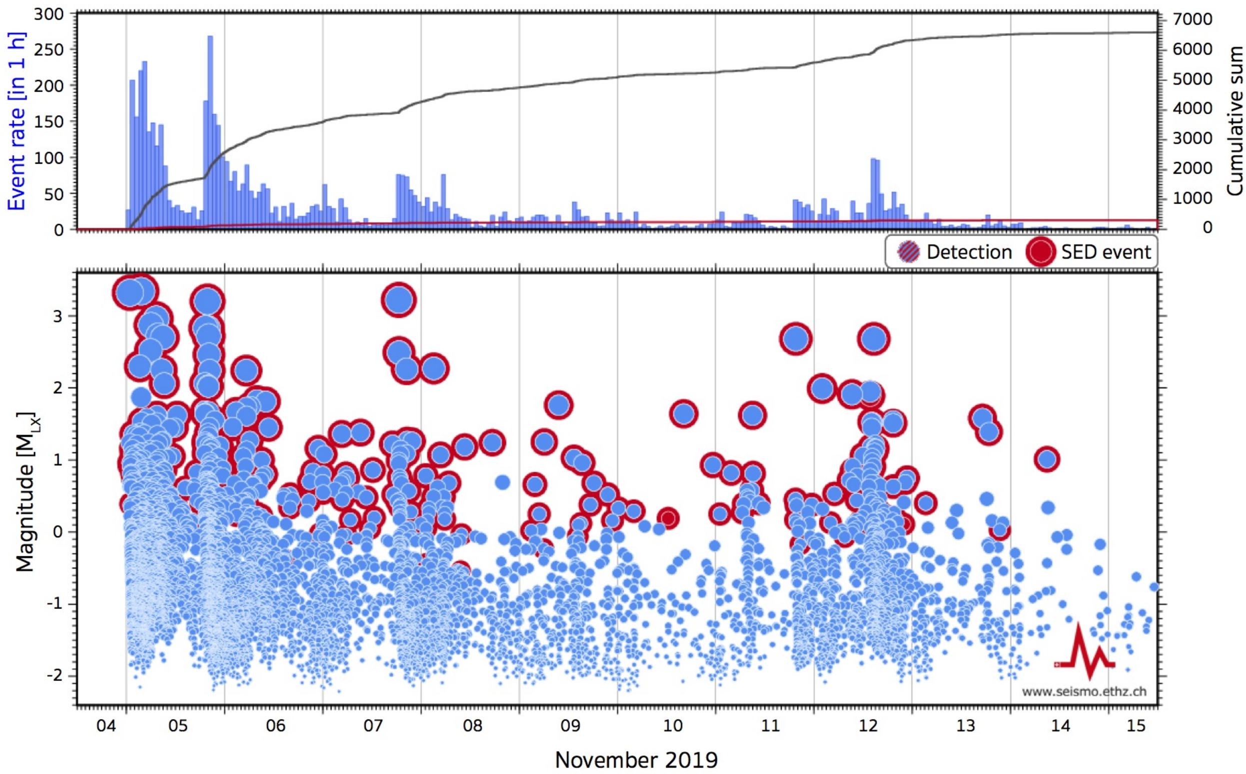


**Figure 6.6:** *Results of template matching technique for swarm detection in Valais. Blue: all events; red edge: classical detections. Source: SED website, www.seismo.ethz.ch.*

the Swiss canton with the highest seismic activity, is presented (Fig. 6.6) to show template matching that greatly improves the earthquake detection capacity. A total of more than more than 300 earthquakes of local magnitude ranging from 0.1 to 3.3 were detected in November 2019, north of Sion, of which 16 were perceived by the population. After template matching, thousands of events were identified with magnitudes as low as -2.0 (Fig. 6.6).

Template matching approached applied to NSSN data by is a promising target. While nearly automatic processing can be launched, careful analysis is needed to avoid false directions or over-interpretation. A better understanding of fault geometries and seismic swarms in the study area would be of high interest, especially following the detection of such transients and smaller scale structures in Far-West Nepal (Hoste-Colomer et al., 2018).

### 6.3.3 Tomography

Even with the limited bandwidth of RS1D seismometers some seismic tomography approaches can be carried out with the NSSN, both with local seismic events and with background noise.

Local earthquake tomography is a common tool for imaging subsurface structure in seismically active areas with a seismic network directly above. In its initial step, a 1-D reference velocity model is determined (Kissling et al., 1994). In a following step, a 3-D velocity model can be deduced (e.g., Haslinger and Kissling, 2001). The NSSN is suitable for P-wave velocity tomography, while S-wave tomography would be more challenging due to the lack of horizontal component records. Given that local earthquakes nucleate mostly around the MHT at ca. 15 km depth, imaging the lower crust would require recording events at larger offsets. Results could reveal local sedimentary basins (e.g. around Pokhara) and along-strike variations of the collisional structure.

Ambient noise tomography is a more recently developed approach based on the seismic noise generated mainly as a result of coupling between the solid Earth with the oceans and the atmosphere. The use of coherent seismic noise signals recorded by multiple stations allow imaging the Earth's subsurface structure (e.g., Snieder, 2004) without the use of seismic sources. Ambient noise tomography works in regions without local earthquakes, but its depth penetration depends on the spatial aperture of the seismic network (e.g., Lehujeur et al., 2018). The final result of ANT are shear-wave velocity models, which would be complementary to P-wave models from LET. For the NSSN, the depth penetration of this method may reach the base of the crust in the middle of the network, and would map well the upper part of the crust.

### 6.3.4 NSSN extension

The current NSSN covers about one fifth of Nepal, in its central region, called Western Nepal, which is its relative location from the capital. An extension of the NSSN in the future would be most natural, and can be thought of in different ways, either geographically, or institutionally.

Geographical extension of the network is aimed as about four fifths of Nepal is not covered by the network, and no similar project is initiated there. The priority of network extension is Far-West Nepal, the least developed part of the country having the highest seismic hazard, and far from the federal capital which means less opportunity for programs and outreach. The area is seismically active (e.g., Hoste-Colomer et al., 2018) and lies in the seismic gap where a great earthquake is expected. We know, it is not an easy task to extend the network in Far-West Nepal as the region is mostly reachable only by dirt and unpaved roads, without established internet connection, and possibly with no electricity in remote sites. Since the earthquake awareness in this region is expected to be very low, it is very important to extend the network with high motivation, even if this requires more fieldwork and more steps to succeed. We have already received comments from people from Far-West Nepal mentioning that they are interested to join our program, which is good as their participation will ultimately help for the local implementation. To move towards the west with the NSSN extension is a priority, however, the entire country could be covered by the network at some point. We estimate that an additional 60 - 70 sensors are needed to cover all Nepal at a similar station density as the current region.

The institutional aspect for the network extension is to motivate universities and colleges to participate in our program and to encourage them to install a low-cost seismometer at their locations. Even in larger cities and in the area of the current network, we could densify the NSSN this way. This purpose not only enhances the earthquake detection capacity but also allows teaching seismology to many university students. On the other hand, we have seen several green signals from the local government during the NSSN installation and some schools have also received financial support from them to run the program. As a citizen science implementation, it would be good to include local government offices in the list of possible network extension locations. The focus should continue serving a dual purpose: earthquake recording and education to citizens. If authorities from the local governments become convinced about the seismometers' application in communities being useful, they could dedicate a budget to purchase further instruments.

Another natural development of the NSSN would be to develop an earthquake early warning module in Nepal. The installation of a dense network in the given area is the first step to construct the warning system. In addition, very efficient communication pathways and a dedicated computer center is required to run early warning and to issue alerts. This needs to be steered by a single authority in the country, ideally the National Seismological Centre, and we consider this as an important mid-term plan for Nepal. One of the most crucial information which needs to be updated in Nepal is the local velocity model over the entire county. For this purpose, any type of seismic data, from permanent to temporary, from broadband to low-cost, should be used to achieve 3D results.

The concept of NSSN extension across Nepal remains a non-trivial challenge and also a promising future direction to truly bridge between geoscientists and citizens. Adequate completion of this extension would improve the earthquake detection and location capability, along with the openly available data for further studies. Most importantly, successfully executed educational and seismological application of this thesis could also trigger the governmental authorities, the academic communities, and can ultimately influence the non-scientists community in Nepal.

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