MONITORING OF SEISMIC EVENTS IN THE CENTRAL ANDEAN REGION

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ABSTRACT

Where the crust of the earth is very thick, for example in the Andean region of South America, the locations and depths of seismic events given by reporting agencies are systematically wrong, because these agencies use models of the earth with crusts of 24-, 33- and 35-km thickness, whereas the earth's crust in western Bolivia reaches a thickness of 72 km. In addition, the International Data Centre commences its location of events in the central Andean region with a location from the Yellowknife array in western Canada. By this method it is difficult to read accurately the arrivals of events of magnitude less than 4. We have used local seismic stations in the region of Bolivia and a three-dimensional model to locate seismic events in the central Andean region. We use the Podvin-Lecomte method to calculate the least-time paths from points in the grid to the seismic stations and the maximum of the Tarantola-Valette probability density function to calculate the seismic event location. Our grid spacing is 5 km and we make an iteration at one tenth of 5 km. Our assumption of a P- to S-wave velocity ratio of 1.76 means that the least-time paths of P and S waves are the same, but clearly, under the Western Cordillera, this assumption is also systematically wrong. Between latitudes of 15 and 28 degrees S, we have noticed that the larger, active (since the beginning of the Holocene) volcanoes are approximately over the revised 125-km depth contour of the Nazca slab. We are strongly reducing S-wave velocities in this part of the model. Also, recent work with P-to-S converted seismic waves has shown a 10- to 20-km thick intra-crustal low-velocity zone extending from the Eastern Cordillera, where the Brazil Shield is underthrusting, to the Altiplano in Bolivia and the Puna in Argentina. We are reducing P- and S-wave velocities in this extensive intra-crustal region also.

KEY WORDS: earthquake location, central Andean region, Western Cordillera, low velocity zone.

OBJECTIVES

The objectives of this study were: i) to test a proposed three-dimensional P- and S-wave velocity model for the region of southern Peru and western Bolivia; ii) to determine the mislocation for earthquakes of intermediate depth outside the Bolivian seismic network (and including some Peruvian stations); and iii) to compare different velocity models and earthquake location methods for the region.

RESEARCH ACCOMPLISHED

Introduction

The region of study is located above the segment of the subduction zone dipping ENE normally about 30° (Barazangi and Isacks, 1976; Sacks, 1977; Cahill and Isacks, 1992).

The western central Andes region has a morphostructural zonation with two zones: i) the low Pacific lands (altitudes up to 2500 m), comprising the Coastal Cordillera and the Longitudinal Valley; and ii) the high Andes (altitudes between 2500 and 7000 m), comprising the Western Cordillera, the Altiplano, the Eastern Cordillera and the Subandean zone (Figure 1).

The use of worldwide teleseismic data, for example the bulletins of the International Data Centre, permits us to define the general patterns of seismicity (Barazangi and Isacks, 1976, 1979; Chowdhury and Whiteman, 1987; Cahill and Isacks, 1992), but a higher precision of location is obtained by a local network with close azimuthal coverage. However, lateral variations in the Wadati-Benioff zone caused by the descending high-velocity slab introduce location errors and a smaller thickness of the Wadati-Benioff zone than the actual thickness (McLaren and Frohlich, 1985). Commonly, location errors are smaller for events with focal depths less than 50-km depth, because the rays spend only a short time traveling within the slab. In contrast, rays from deeper events may travel long distances in the slab; this causes them to be grossly mislocated by local networks (Engdahl et al., 1977; Fujita et al., 1981; Frohlich et al., 1982).

The permanent Bolivian local seismic network has sparse coverage in the Peru-Bolivia border region (Figure 1) and to find more precise locations we need to include some stations of the Peruvian net.

Data

The data were recorded by the permanent telemetric Bolivian local seismic network (Figure 1) and some stations of Peruvian net; these data cover the period from January 2000 to December 2000, with magnitude mb greater than 3.0.

The uncertainties of picking P arrival times were less than or equal to 0.05 s and the uncertainties of picking S arrival times were less than or equal to 0.10 s (Figure 2). The P to S-wave velocity ratio was taken to be equal to 1.76.

Table 1. Station coordinates of the Bolivian permanent telemetric network, with some Peruvian seismic stations

CODE	LATITUDE °S	LONGITUDE °W	ALTITUDE M
BBOB	16.1443	68.1329	3960
BBOD	16.6374	68.5981	4230
BBOE	16.8127	67.9821	4325
BBOF	16.9740	68.3380	4480
LPAZ	16.7829	68.1307	4740
CON	15.4400	69.4300	3900
LYA	18.1350	70.8500	363
SNG	16.5700	72.7150	161
TAM	13.4780	71.8590	3858
TOQ	17.3070	70.6430	2586

Hypocenter location method

Two different hypocenter location methods were used: i) the conventional method Hypocenter version 3.2 (Lienert et al., 1986); and ii) the 3-DGRIDLOC method (Wittlinger et al., 1993; Ayala, 1997).

This latter method is a combination of two tools: First, the PL method (Podvin and Lecomte, 1991) is used to solve the forward problem, that is, to calculate the first arrival times at the cells of the seismograph stations from each of the cells of a three-dimensional velocity model. This method was inspired by the approach of Vidale (1988; 1990). In the ray approximation, wave propagation is described by the eikonal equation

$$(\nabla t)^2 = s^2$$

where s is the slowness of the medium (inverse of wave velocity) and t represents the arrival time of a wavefront at a point. According to the classical ray approximation (asymptotic approximation of the wave equation at infinite frequency), wavefronts are treated as propagating discontinuities (represented as isochrons). The approach of Vidale (1988; 1990) relies on a finite difference approximation of the eikonal equation. With the PL method, wavefronts rather than rays are propagated in the model. First arrival times are computed relying on a systematic application of Huygens' principle in the finite difference approximation. Such an approach takes into account transmitted and diffracted body waves and head waves. Local discontinuities of the gradient of the time field of the first arrival, for example, caustics, are built as intersections of locally independent wavefronts. As a consequence the PL method provides accurate travel times of the first arrivals in the presence of severe, arbitrarily shaped velocity contrasts.

Secondly, a nonlinear algorithm from Tarantola and Valette (1982) uses a probability density function to solve the inverse problem; that is, from the first arrival times at the seismograph stations, it calculates the cell that most probably contains the earthquake. The process is repeated with cells reduced in volume by a factor of 1000.

By direct methods, such as 3-DGRIDLOC, based on a hypocenter searching in a three-dimensional mesh, when the velocity model is known, earthquake outside the network, where there is sparse coverage of seismograph stations, can be reliably located (Nelson and Vidale, 1990).

Velocity models

To relocate the earthquakes we used two different velocity models: i) a conventional velocity model of flat homogeneous layers (Table 2); and ii) an approximately three-dimensional velocity model for the region, with a descending high-velocity slab, dipping ENE at approximately 30°.

Table 2. Velocity structure

Layer thickness (km)	**P velocity** (km s^{-1})
10	5.0
25	6.0
25	6.6
	8.0

The three-dimensional velocity model corresponds to the western part of the three-dimensional velocity model proposed for the region of the Bolivian Andes (Ayala, 1997; Ayala and Drake, 1997). The model comprised 150 x 100 x 70 cubic cells of approximately 5-km size (Figure 1), defining a cubic volume of 750 km in longitude, 500 km in latitude and 350 km in depth with different velocity structures for each of the morphostructural zones (Schmitz, 1993; Wigger et al., 1994; Romanyuk et al., 1999). The depth of the Moho was taken from the Airy compensation model (Schmitz, 1993; Schmitz et al., 1997). The shape of the slab was taken from the geometry of the Wadati-Benioff zone (Cahill and Isacks, 1992), with a thickness of 80 km and a velocity 2.7 per cent faster than the surrounding mantle velocity (Engdahl et al., 1995; Dorbath et al., 1996). For the mantle, at depths between 200 and 650 km above and below the slab, we took the velocity of the *iasp91* model (Kennett and Engdahl, 1991).

Results

Most of the earthquakes relocated are inside the Bolivian and Peruvian seismic nets along a narrow band of seismicity related to the subducted Nazca plate.

The relocations of the earthquakes using the method Hypocenter, version 3.2, with all stations, are different to locations of the IDC bulletins. The average computed horizontal mislocation is less than or equal to 10 km, and the average computed vertical mislocation is less than or equal to 20 km, compared with the locations of the IDC bulletins. The residuals of all relocations, with and without the Peruvian seismic stations, are similar, and proved to be relatively insensitive to the amount of mislocation, compared with the location of the IDC bulletins. The average computed horizontal and vertical location errors are less than or equal to 15 km. In general, the vector of mislocation is in the northeast-southwest direction.

The relocation of events using the 3-DGRIDLOC method and a three-dimensional velocity model, with and without the Peruvian seismic stations, also proved to be relatively insensitive to the amount of mislocation, compared with the locations of the IDC bulletins, and showed average computed horizontal and vertical mislocations less than or equal to 10 km, compared with the locations of the IDC bulletins. The larger mislocations are in the northern part of the region, while, in the southern part of the region, the mislocations are smaller. When the data of the Peruvian seismic stations are introduced, the residuals increased.

CONCLUSIONS AND FUTURE PLANS

Conventional location velocity models, for example, those of Hypocenter, version 3.2, introduce systematic location errors in subduction zones, both because the structure of the earth is very different from those of the models in these regions, and because, in this particular comparison of locations, we assumed a P- to S-wave velocity ratio of 1.76, whereas clearly, under the Western Cordillera, this assumption is also wrong. The residuals, with and without the Peruvian seismic stations, were similar and proved to be relatively insensitive to the amount of mislocation, compared with the locations of the IDC bulletins.

For the three-dimensional 3-DGRIDLOC method, our assumption of a P- to S-wave velocity ratio of 1.76 meant that the least-time paths of P and S waves were the same, and this saved computing time, but it was a wrong assumption. The three-dimensional velocity model is a more realistic approximation to the velocity structure of the region. The model and the three-dimensional 3-DGRIDLOC method have allowed us to obtain locations more like those of the IDC bulletins, especially in the case of earthquakes outside the network, mainly in the southern part of the Peru-Bolivia border region. The active volcanic chain of the Western Cordillera reduces the S-wave velocities in this part of the model; this fact is reflected when the Peruvian seismic data are introduced, and the locations using 3-DGRIDLOC method and three-dimensional velocity model show larger residuals. The location for the southern part of the region shows smaller mislocations compared with the northern part of the region; this fact shows that the three-dimensional velocity models is more appropriate in the southern part of the region than in the northern part of the region

In future work we will: i) continue to revise the locations of earthquakes in the whole of the Bolivian Andes; ii) quantify more precisely, using the data of temporary seismic nets, the differences of our locations from those of the bulletins of the IDC; and iii) improve the three-dimensional velocity model for the region, in order to take into account the anomalous velocity regions. Besides the difficulties of the S-wave velocities beneath the volcanoes of the Western Cordillera, recent work with P-to-S converted seismic waves has shown an intra-crustal low-velocity zone, of thickness of 10 to 20 km, extending from the Eastern Cordillera, where the Brazil Shield is underthrusting, to the Altiplano in Bolivia and the Puna in Argentina.

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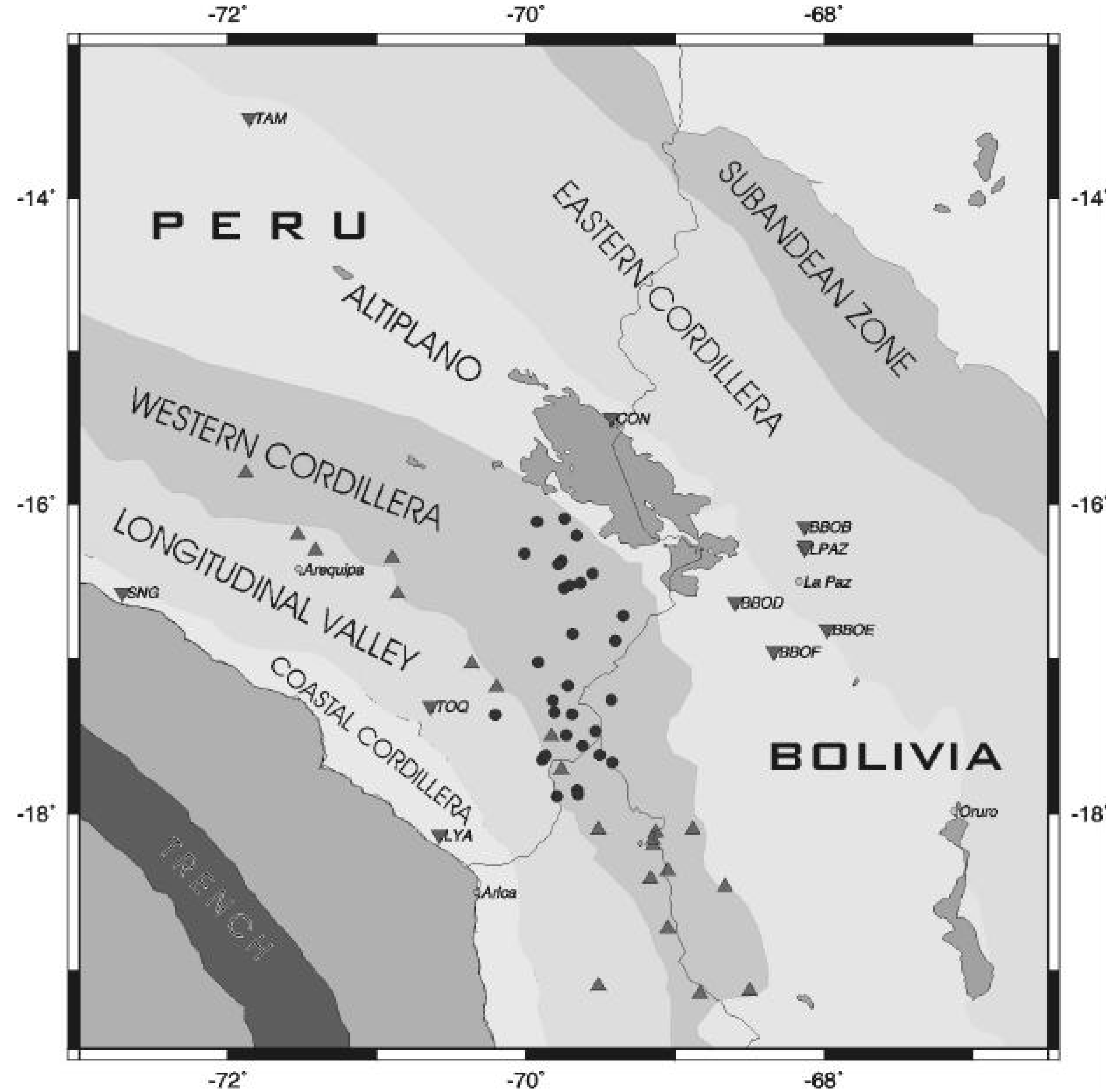

Figure 1. Map of the morphostructural units for the western central Andes and the distribution of seismograph stations of the Bolivian permanent telemetric network, including some Peruvian seismic stations (inverted triangles); the triangles represent the active volcanoes in the region; the white small circles represent the main cities; the dark circles represent the epicenters of the earthquakes recorded during the period January 2000 to December 2000, with magnitudes mb greater than 3.0.

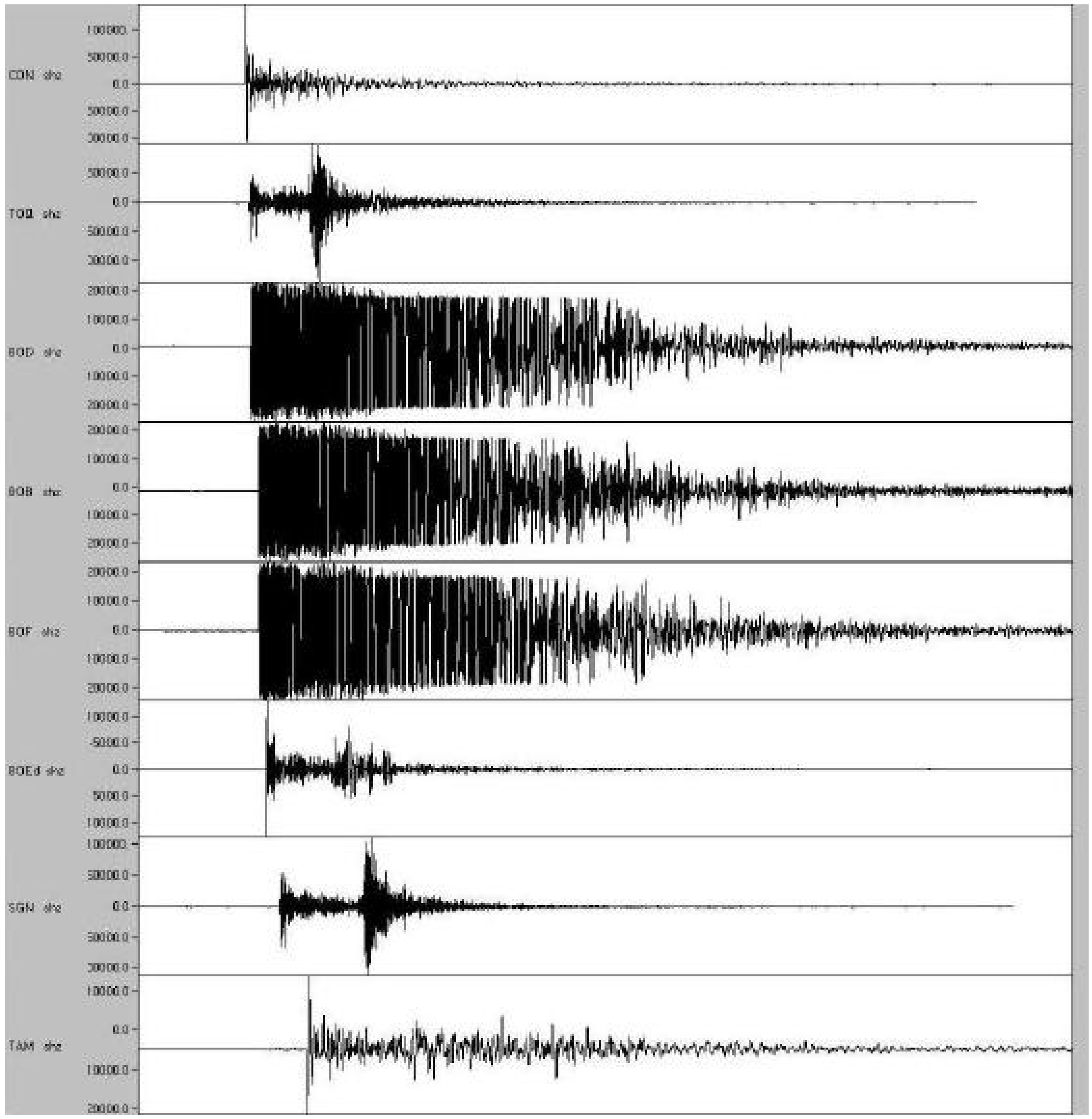

Figure 2. Example of short-period seismographs of 25 April 2000 earthquake recorded by the Bolivian seismic network and the Peruvian seismic station located in western central Andes.

VALIDATION AND GENERATION OF REFERENCE EVENTS BY CLUSTER ANALYSIS

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ABSTRACT

High-resolution cluster analysis (multiple-event relocation) of earthquakes and other seismic sources is developed as a tool for assembling catalogs of reference events, especially those whose locations can be determined with an accuracy of 5 km or better [Ground Truth (GT) 5]. We use the Hypocentroidal Decomposition (HDC) method of Jordan and Sverdrup (1981), which is well suited to the rigorous statistical analysis required for this task. Candidate reference events typically arise from local seismic networks and from temporary deployments for aftershock studies that can yield very high-resolution hypocenters that, nevertheless, must be validated. We utilize arrival time data (as reported to the International Seismological Centre and to the U.S. Geological Survey's National Earthquake Information Center) at regional and teleseismic distances in the cluster analysis to validate candidate reference events, and in some cases, to generate new reference events.

HDC analyses have now been performed on a number of earthquake and explosion sequences in Eurasia and Africa, resulting in reference events with locations known to GT5 accuracy. In this paper we review and evaluate our analyses of these clusters to date, and address problem areas. In particular, we find that some candidate reference events cannot be validated because either the reported local network solutions are in error, or the coverage of reported arrival times used in the HDC analysis is not sufficient to constrain the locations. Some discrepancies may arise when local networks locate small precursors or low-energy early stages of rupture in larger earthquakes, while teleseismic stations record only the main pulse of energy release. We have found several cases in which there appear to be systematic biases in the time base used for local network solutions. In another case, we obtained "reference event" locations from two different sources for the same cluster. The two sets are similar enough that HDC cannot be used to discriminate between them, yet different enough to prevent either set from being accepted at GT5 accuracy. Our experiences highlight the importance of a thorough and many-faceted validation program for candidate reference events.

KEY WORDS: reference events, cluster analysis

OBJECTIVE

The primary objective of this research effort is to develop a comprehensive reference event database with validated travel-time information for regional seismic phases recorded by International Monitoring System (IMS) and surrogate stations in Asia and north Africa. This database can be used to support the calculation of regional travel-time curves and source-specific station corrections.

RESEARCH ACCOMPLISHED

Introduction

In this report, we discuss the results of cluster analyses on earthquake and explosion sequences in Eurasia and northern Africa using phase data reported to the ISC and NEIC. All of the events studied have magnitudes of 3.5 or greater. In most cases, reference event data are available from short-term portable seismograph deployments following the initiation of seismic activity. The HDC analyses produce new locations that are defined by "cluster vectors" in space and origin time, relative to the centroid, which is then located in the traditional manner to yield absolute locations and origin times. If one or more reference events are included in