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An improved P-wave velocity reference model for Costa Rica

Ronnie Quintero[1,2] and Edi Kissling[3]
[1] *Universidad Nacional de Costa Rica, Costa Rica*
[2] *Department of Earth Sciences, Uppsala University, Sweden*
[3] *Institute of Geophysics, ETH Zürich, Switzerland*

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RESUMEN

Derivamos un modelo de velocidad unidimensional para la onda P en Costa Rica, el cual puede servir en la rutina de localización de eventos sísmicos y como modelo de referencia para tomografía en 3 dimensiones. La inversión para la velocidad es realizada usando 822 sismos con buena ubicación y 14 774 observaciones de la onda P, las cuales fueron obtenidas combinando datos de tiempos de arribo de 10 335 eventos en el periodo 1984-1997 colectados por el Observatorio Vulcanológico y Sismológico de la Universidad Nacional de Costa Rica (OVSICORI-UNA) y 3510 eventos en el periodo 1992-1998 colectados por la Red Sismológica Nacional (RSN). Durante el proceso de fusión, se tomó un cuidado estricto para reducir el número de errores en los datos, y en particular, para adaptar, corregir y completar los parámetros de las estaciones sísmicas. Un modelo de velocidad unidimensional es prerequisito para tal proceso de fusión cuando la consistencia y calidad tienen prioridad sobre la totalidad del resultante juego de datos. Los datos finales para el periodo 1984-1998 en Costa Rica consiste de 11 848 eventos locales con 13 2331 observaciones de ondas P y 86 018 de ondas S.

PALABRAS CLAVE: Fusión, relocalización conjunta de hipocentros, parámetros de velocidad, velocidad de la onda P.

ABSTRACT

We derive a P-wave 1D-velocity model for Costa Rica that may serve for routine high-precision earthquake location and as initial reference model for 3D seismic tomography. The velocity inversions are performed using 822 well-locatable events together with 14774 P-wave observations obtained by merging routine travel time data from 10 335 earthquakes in the period 1984 to 1997 collected by the Universidad Nacional de Costa Rica (OVSICORI), and 3510 earthquakes in the period 1992 to 1998 collected by the Red Sismológica Nacional (RSN) in Costa Rica. Special care is taken during the merging process to reduce the number of errors in the data and, in particular, to update, correct, and complete the station parameter list. Consistency and quality are given priority over completeness of the resulting data set. The final data set for the period 1984 to 1998 in Costa Rica consists of 11 848 local events with 13 2331 P-wave and 86 018 S-wave observations.

KEY WORDS: Merging travel time data, P-wave velocity model for Costa Rica, joint inversion hypocentral and velocity parameters.

INTRODUCTION

Uniform high-precision earthquake location is of importance in a seismically active area like Costa Rica (Figure 1) where the seismic data base is a prerequisite for tectonic interpretation and seismic hazard assessment. Recent tomographic applications (e.g., Protti *et al*., 1996; Yao *et al*., 1999; Sallares, 1999) have used local and teleseismic earthquake sources to study the three-dimensional lithospheric structure beneath Costa Rica. In general, their tomographic results correlate well with surface structure such as the chain of active volcanoes. These studies also document the great potential of passive seismic tomography to unravel the structure of this seismically and volcanically active subduction zone. These tomographic studies of the crust and uppermost mantle, however, are particularly hampered by the lack of a sufficiently large data set of high quality and by a significant amount of large errors in the existing data sets. In Costa Rica, two separate seismic networks (Universidad Nacional de Costa Rica, OVSICORI-UNA, and Red Sismológica Nacional, RSN) exist and collect seismological information for the same region (Figure 2). Each network follows different ways of recording and treating the data and uses different velocity models for routine earthquake location. Different phase identifications, variable travel time observations and quality assessments, and different event locations make the merging procedure a difficult task.

In this study we compile a clean phase data set for the Costa Rica region, using information from two independent seismological networks. Consistency and quality of the merged final data set are given priority over completeness. In the case of conflicting and suspicious information or when an apparent error in one of the original data sets cannot be recovered, all data of this particular event are deleted.

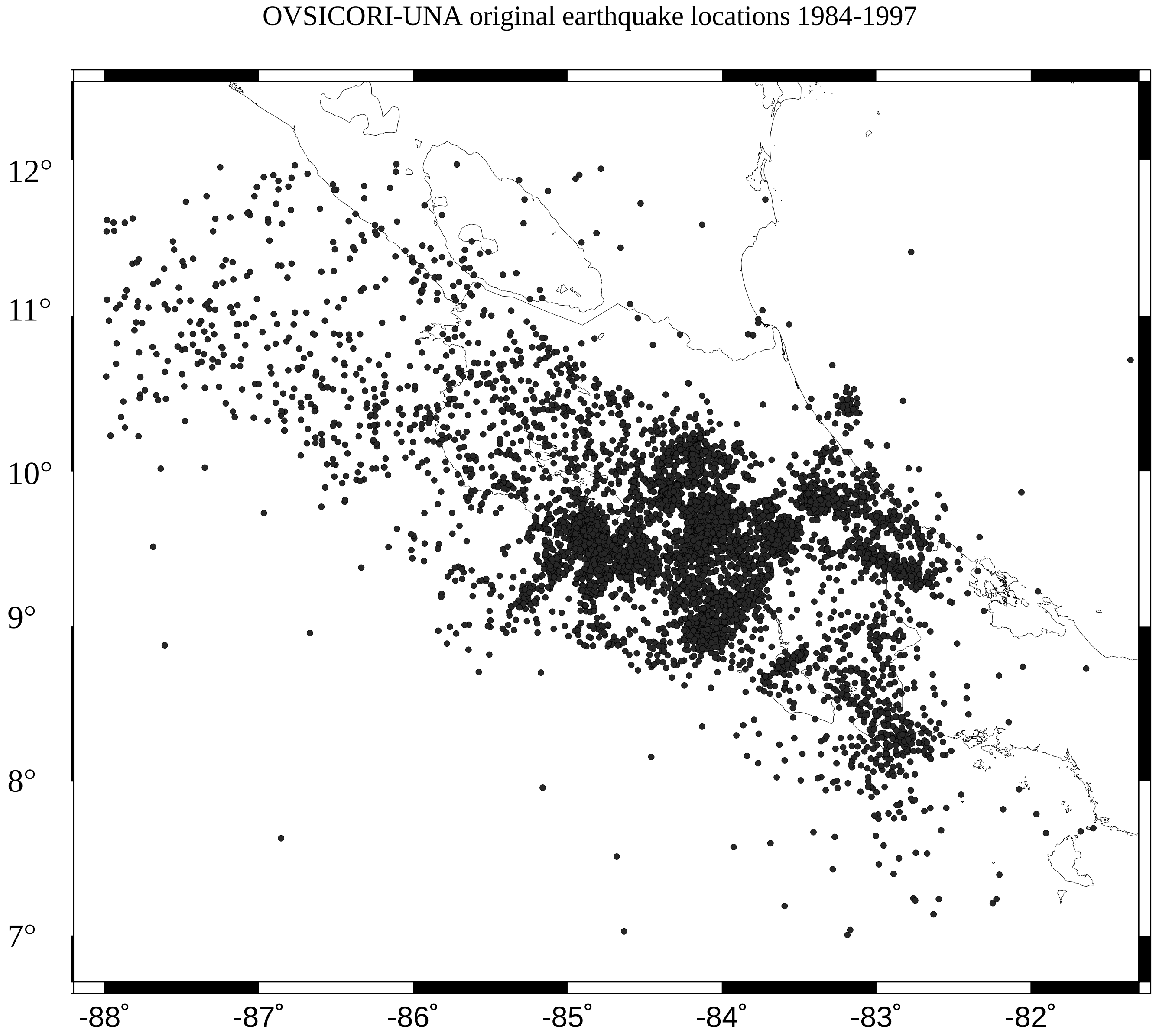

Fig. 1. Seismicity between 1984 and 1997 in Costa Rica recorded by the Observatorio Vulcanológico y Sismológico de Costa Rica network administered by the Universidad Nacional (OVSICORI-UNA).

The travel time of a seismic wave is a non-linear function of hypocentral parameters and seismic velocities sampled along the ray path between source and station. This dependency is called coupled hypocenter-velocity model problem (Crosson, 1976; Kissling, 1988; Thurber, 1992). For a 1D-velocity model with station corrections it can be solved for a large number of events iteratively by program VELEST (Kissling *et al.*, 1995a).

In the standard earthquake location procedure, the velocity parameters are kept to a priori values and the observed travel times are interpreted by perturbation of the hypocentral parameters only. Neglecting coupling between hypocentral and velocity parameters during the location process can introduce systematic errors in hypocenter locations (Thurber, 1992). Furthermore, error estimates strongly depend on the assumed a priori velocity structure (Kissling, 1988) and normally are largely underestimating the true location errors (Kradolfer, 1989, Husen *et al.*, 1999). Precise hypocenter location and error estimates, therefore, demand the simultaneous inversion of velocity and hypocenter parameters as in the VELEST program (Kissling *et al.*, 1995a). The minimum 1D velocity model (for definition of the term and for calculation guide of a minimum 1D velocity model, see Kissling 1988, Kissling *et al.*, 1994, respectively) is obtained by trial-and-error for various initial velocity and hypocentral parameters and for different damping. It represents a model that leads to a minimum

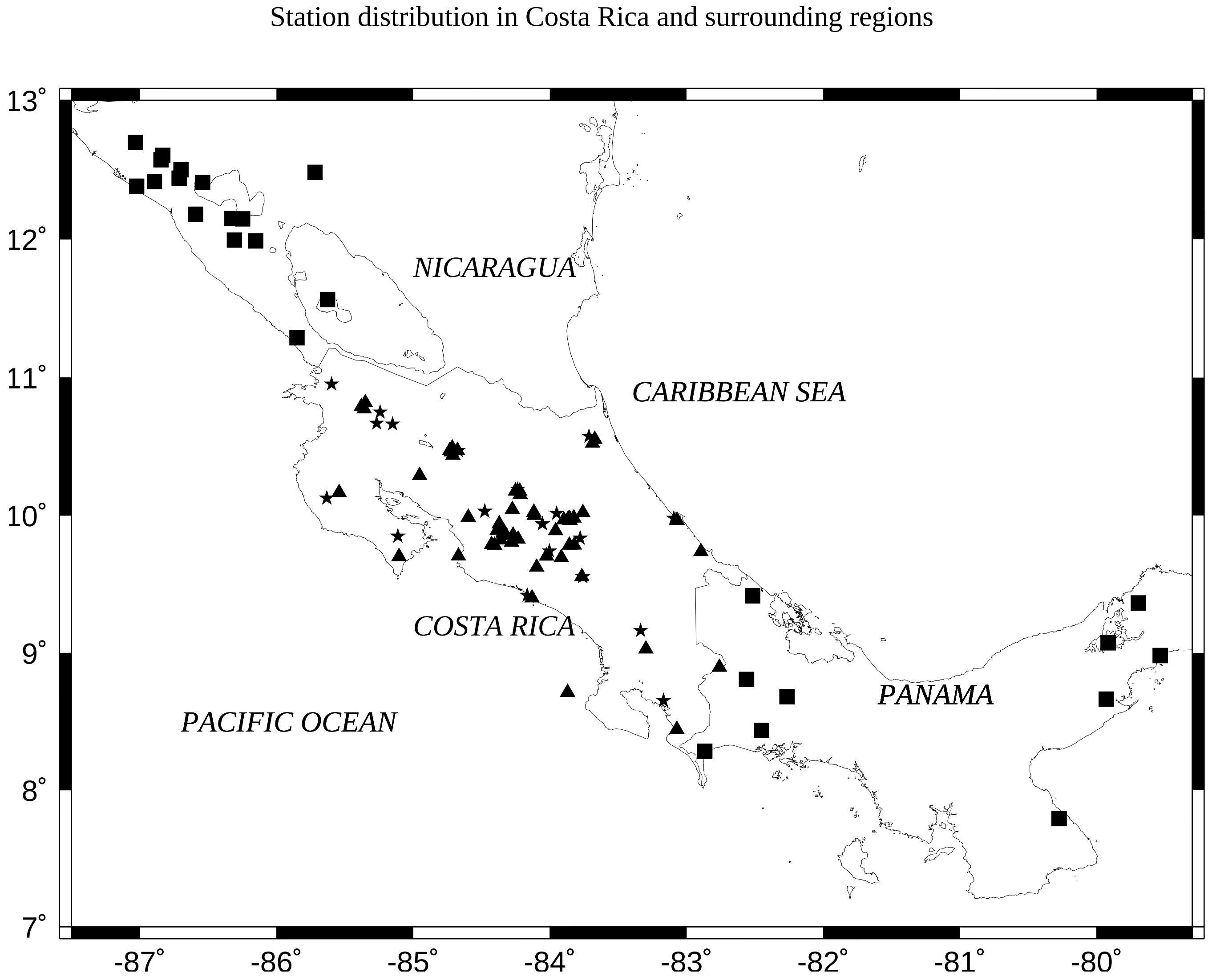
Station distribution in Costa Rica and surrounding regions

Fig. 2. Station distribution in Costa Rica and surrounding regions. Triangles: OVSICORI-UNA; Stars: Red Sismológica Nacional de Costa Rica (RSN); Squares: stations of neighboring networks reporting to the Central America Seismic Center (CASC).

average RMS value for all earthquakes and closely reflects the a priori structural information obtained, e.g., by controlled source studies. To account for lateral variations in the shallow subsurface, station corrections are incorporated in the inversion process.

We derive a so-called minimum 1D P-velocity model (Kissling, 1988) that may serve as a reference model for 3D seismic tomography and for routine earthquake location in Costa Rica for OVSICORI-UNA and RSN networks. The model will be calculated using selected well-locatable events from a merged data set for the period 1984 to 1998 from both OVSICORI-UNA and from RSN. Such 1D-velocity models with corresponding station corrections are the result of simultaneous inversions of a large quantity of high-quality data, for both the velocity model and the hypocentral parameters. Since results of this inverse problem are ambiguous, different velocity models with similar residual variance are obtained. The one that most closely reflects the a priori information about the near-surface structure and that leads to a minimum average RMS value for all earthquake locations is selected as reference model and called the 'Minimum 1D model' for Costa Rica.

LOCAL EARTHQUAKE DATA AND SEISMIC STATIONS IN COSTA RICA

The data used in this study were collected from the Observatorio Vulcanológico y Sismológico de Costa Rica network**,** administered by the Universidad Nacional (OVSICORI-UNA)**,** and the Red Sismológica Nacional de Costa Rica (RSN), network administered jointly by the

Universidad de Costa Rica (UCR) and the Instituto Costarricense de Electricidad (ICE). Surrounding these two networks are other Central American national and regional networks that record seismic events in the region. All networks send information to the Central America Seismic Center (CASC), which is situated in Costa Rica (Alvarenga *et al.,* 1998). The RSN data set used in this study was collected from the CASC seismic center. The seismic sources are confined to the area 7°N-12°N latitude and 82°W-88°W longitude, and a depth range from surface to 300 km.

The OVSICORI-UNA and RSN seismic networks are telemetered networks and are equipped mainly with short-period (1Hz) vertical-component seismometers. From 1992, network data are being recorded digitally at the recording centers (50Hz sampling rate). The stations are distributed around the country, in a few cases very close to each other, and cover almost entirely our study area. The RSN network has been operating since 1982 and the OVSICORI-UNA network since 1984. In this study we use OVSICORI-UNA data from the period 1984 to 1997 and RSN data from the period 1992-1998 (Figure 3). We merge data from both networks for the period 1992 to 1997.

The principal data gathered by both networks are the first P and S-wave arrival times, polarities and coda duration from local and regional earthquakes. We extract mostly P and a few S-wave arrival times in combination with a factor describing the quality of the observation. The wavelet onsets are described as either ”i” (for impetus) or ”e” (for emersio) and are assigned relative weights between 0 and 4 depending on the quality of the recorded seismogram (Lee and Lahr, 1975). The two networks not only use different weighting schemes but also different velocity models (Fig-

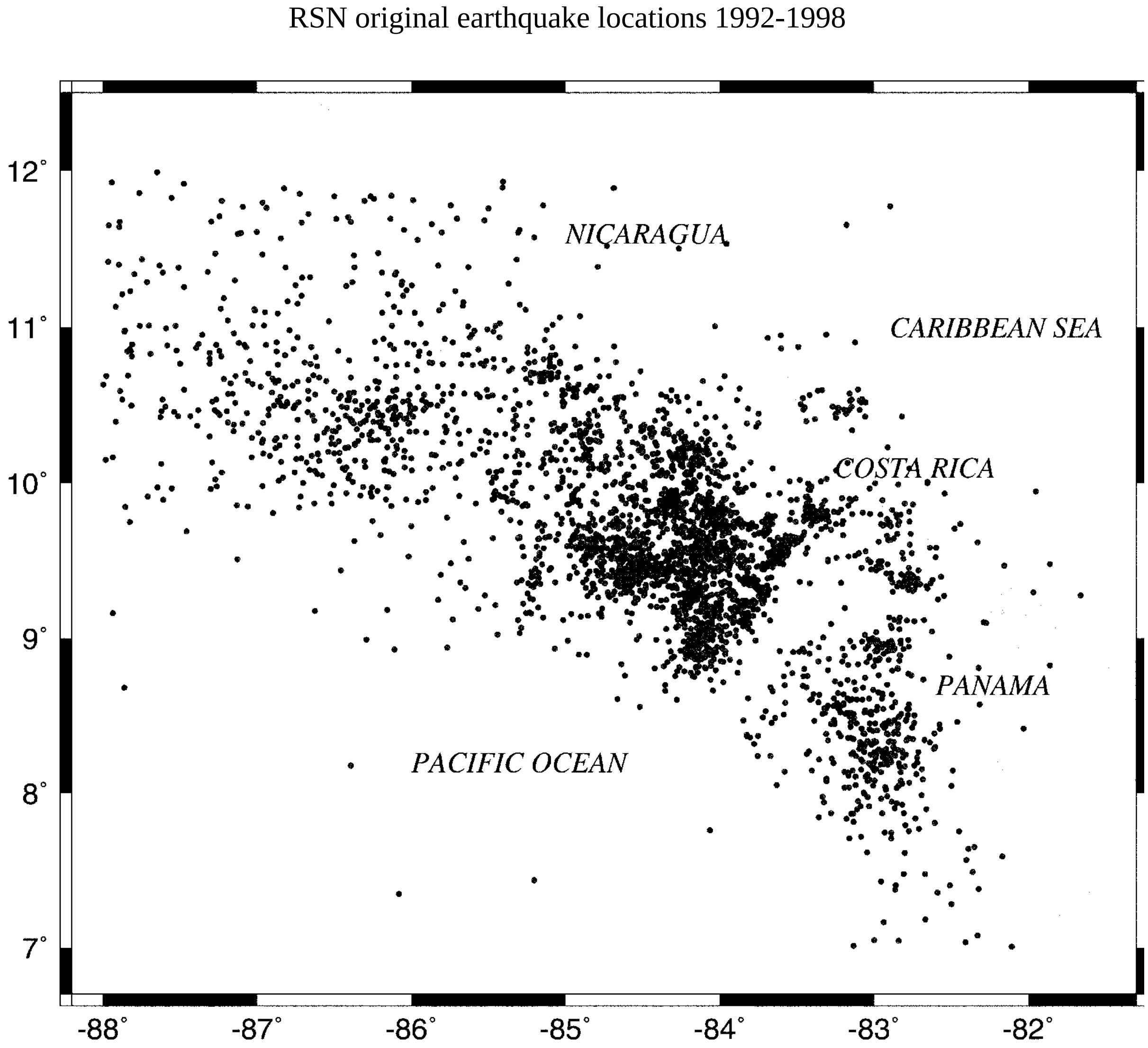

Fig. 3. Seismicity between 1992 and 1998 in Costa Rica recorded by the Red Sismológica Nacional de Costa Rica (RSN) station network.

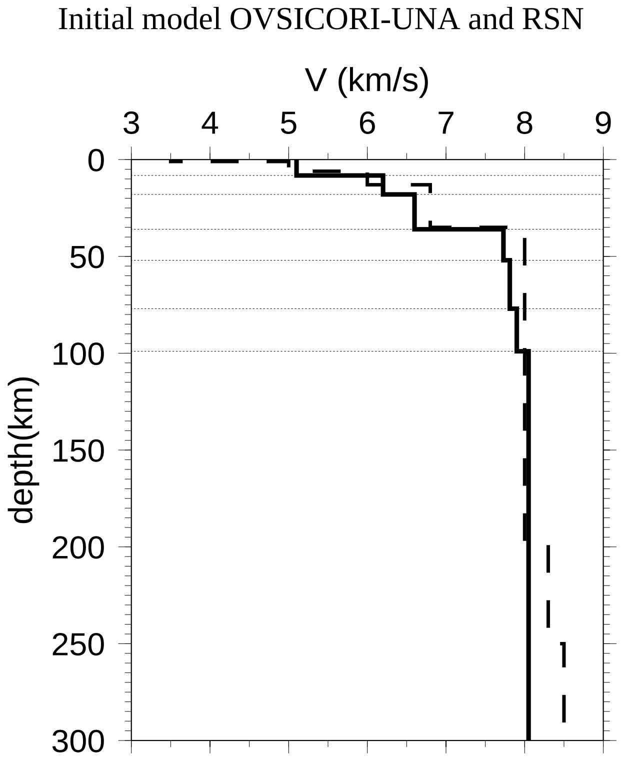

Fig. 4. P-wave velocity models for Costa Rica. 1D-models used for routine earthquake location by OVSICORI-UNA (solid line) and RSN (broken line).

ure 4) and different version computer programs for routine earthquake location. During the period 1984 to 1992, the routine earthquake locations conducted by OVSICORI-UNA were calculated using the program HYPOINVERSE (Klein 1984) and since 1992, they are calculated using the program HYPOCENTER provided by the SEISAN software package (Lienert and Havskov, 1995; Haskov, 1997), for both networks.

Though RSN and OVSICORI-UNA are two independent station networks that routinely obtain and list information from other networks. A major source of systematic errors in travel time data in general, and when merging data from two networks in particular, is an incomplete, outdated, or otherwise incorrect station list. For this reason, we first compile a station list with all permanent and temporary stations that have been operating in Nicaragua, Costa Rica, and Panama. After clarification of ownership for all stations, we ask each seismological service to check the coordinates and the names of their stations. By this process, several mistakes in published station parameters are detected and corrected. In a few cases, mostly for temporary stations, it was not possible to verify the station parameters. Phase data from stations without verified coordinates are deleted from the data set and are ignored in subsequent calculations. The compiled master station list contains all stations with verified parameters (see Table 1).

MERGING OVSICORI-UNA AND RSN DATA SETS FOR THE PERIOD 1992-1997

RSN and OVSICORI-UNA data sets overlap in the period between 1992-1997. Each data set contains phase data exchanged with, and partially modified from, other Central American networks. Phase data exchanged between the two networks of Costa Rica show a significant percentage of modification in arrival times and/or observation weights: The operators may arbitrarily adjust the arrival times or reduce the observation weights for data obtained from the other network without consulting the original seismic signals. As a general rule, we prefer to use the original observations, i.e., those provided by the owner of the station. Data from networks outside of Costa Rica have been obtained through CASC and original observations were not available. In case of multiple reports, preference is given to OVSICORI-UNA reports.

The merging process is described in Figure 5. Recognition of common events is primarily based on similarities in hypocenter parameters (Solarino *et al.,* 1997). After reformatting the original phase data and relocating all events (step 1), the merging process begins with the calculation of good location models (Kissling *et al.,* 1995b). In this step, we calculate good 1D P-wave velocity models using the computer program VELEST for OVSICORI-UNA and RSN, separately. The VELEST routine solves the coupled hypocenter-(1D) velocity model problem for up to 600 local events recorded at up to 120 stations by a series of simultaneous inversion. The velocity model is parametrized by layers of constant velocities; hence, vertical velocity gradients must be approximated by a series of thin layers. For the trial input velocity models, we approximated the velocity-depths functions of the routine location models by OVSICORI-UNA and RSN by a series of 4 km thick layers and calculated appropriate layer velocities that best fit the data. Subsequently, various initial velocity models of different layer thicknesses and different velocities are tested for their performance. For these joint hypocenter-velocity inversions, we selected 600 well-locatable events from each network from the period 1992-1997 with an azimuthal gap ≤160° and at least 9 P-observations for OVSICORI-UNA and at least 6 P-observations for RSN for the inversions. The average RMS of all events is reduced after the first three iterations for the coupled hypocenter-(1D) model inverse problem by more than 40% for OVSICORI-UNA and by 60% for RSN events. The resulting good 1D velocity models for each network (Figure 6) are complemented by station delays and are well-suited for preliminary location calculations by each individual network.

Since the two networks largely overlap geographically, we calculate a common “preliminary” minimum 1D model (step 3, Figure 5) for Costa Rica by employing the best 300 from each data set together with the mean of the UNA 1D

Table 1

Master station list for Costa Rica. Indicated are the station name (4 characters), location (latitude and longitude in degrees), elevation (m), and owning network.

AEL2	10.2305N	84.1717W	1215	OVSICORI
AROL	10.4373N	84.7092W	720	OVSICORI
BJT	10.2162N	84.2960W	1437	OVSICORI
BLCR	9.9393N	84.3698W	530	OVSICORI
BTE	10.1350N	84.2200W	1660	OVSICORI
CAO	9.7012N	85.1033W	263	OVSICORI
CAS	9.9105N	84.6267W	120	OVSICORI
CDM	9.5552N	83.7658W	3470	OVSICORI
CDL	10.5252N	83.6873W	51	OVSICORI
COCR	10.5527N	83.6708W	10	OVSICORI
CHCR	10.0442N	84.2742W	931	OVSICORI
CHI	9.8185N	83.8675W	1220	OVSICORI
CIMA	9.9775N	83.8542W	3370	OVSICORI
COG	9.8638N	83.7667W	1138	OVSICORI
CONO	9.9692N	83.8017W	2620	OVSICORI
CTCR	8.8962N	82.7593W	1620	OVSICORI
DAT	9.6943N	83.9155W	2500	OVSICORI
DPDS	9.8830N	84.3365W	675	OVSICORI
EPA	9.9877N	84.5965W	310	OVSICORI
FICA	9.7375N	82.8945W	204	OVSICORI
GRJO	9.8933N	84.3842W	790	OVSICORI
GYBO	9.8575N	84.2687W	910	OVSICORI
HDC	10.0013N	84.1140W	1157	OVSICORI
HDC2	10.0237N	84.1167W	1220	OVSICORI
HDC1	10.0000N	84.1120W	1150	GEOSCOPE
HIG	9.9523N	84.5462W	230	OVSICORI
IDC	8.7133N	83.8698W	10	OVSICORI
IRZ	9.9745N	83.8657W	3380	OVSICORI
IRZ2	9.9688N	83.8975W	2950	OVSICORI
JTS	10.2908N	84.9525W	340	OVSICORI
LARO	9.7052N	84.0235W	2107	OVSICORI
LBS	9.9817N	83.8233W	3110	OVSICORI
LICR	9.9658N	83.0693W	40	OVSICORI
LNCR	9.9658N	83.0693W	40	OVSICORI
LOLA	10.4900N	84.7137W	550	OVSICORI
MERC	9.8230N	84.3592W	1100	OVSICORI
OCM	9.8897N	83.9573W	1595	OVSICORI
RMCR	9.7845N	83.8572W	1420	OVSICORI
PALO	9.7850N	83.8203W	1440	OVSICORI
PBC	8.4437N	83.0708W	140	OVSICORI
PDCR	9.8285N	84.2320W	1000	OVSICORI
POA	10.1523N	84.2170W	2093	OVSICORI
PTCR	9.7895N	84.4262W	1510	OVSICORI
POCR	9.7843N	84.4042W	1360	OVSICORI
PTRA	9.9642N	83.8517W	3060	OVSICORI
PZOS	9.8067N	84.2800W	750	OVSICORI
RIN	10.7735N	85.3583W	775	OVSICORI
RIN2	10.8185N	85.3495W	1400	OVSICORI
RIN3	10.7908N	85.3787W	900	OVSICORI
SCAR	9.6243N	84.0957W	1525	OVSICORI
SELF	10.4712N	84.7322W	500	OVSICORI
TAPI	9.7727N	83.7942W	1420	OVSICORI
VTU	10.0210N	83.7583W	3329	OVSICORI
WARN	10.4620N	84.7208W	580	OVSICORI
JUD	10.1670N	85.5412W	680	OVSICORI
JUD2	10.1670N	85.5412W	680	OVSICORI
POA2	10.1772N	84.2508W	2500	OVSICORI
POA3	10.1767N	84.2200W	2450	OVSICORI
QPS	9.4012N	84.1302W	83	OVSICORI
QPS2	9.4012N	84.1302W	83	OVSICORI
TIG	9.0290N	83.2970W	763	OVSICORI
TIG2	9.0290N	83.2970W	763	OVSICORI
VACR	10.4720N	84.6755W	360	OVSICORI
PLA	9.7058N	84.6683W	30	OVSICORI
ACR	8.6532N	83.1680W	500	RSN
ACR0	8.6532N	83.1680W	500	RSN
AR6	10.4458N	84.9098W	1010	RSN
AR60	10.4458N	84.9098W	1010	RSN
BAR	9.1633N	83.3358W	375	RSN
CGA	10.0310N	84.4757W	1300	RSN
CGA0	10.0310N	84.4757W	1300	RSN
FOR	10.4717N	84.6700W	400	RSN
FOR0	10.4717N	84.6700W	400	RSN
ICR	9.9800N	83.8312W	3302	RSN
ICR0	9.9800N	83.8312W	3302	RSN
JCR	9.8498N	85.1118W	575	RSN
JCR0	9.8498N	85.1118W	575	RSN
VCR	10.1265N	85.6312W	960	RSN
VCR0	10.1265N	85.6312W	960	RSN
LCR	9.7383N	84.0017W	1400	RSN
LIO	9.9797N	83.0928W	62	RSN
LIO0	9.9797N	83.0928W	62	RSN
VPS2	10.1902N	84.2353W	2570	RSN
VPS	10.1873N	84.2385W	2555	RSN
PRS	9.8505N	84.3112W	1145	RSN
PRS0	9.8505N	84.3112W	1145	RSN
PRS1	9.8795N	84.3640W	1120	RSN
SRA	10.0825N	84.4482W	1160	RSN
SRA0	10.0825N	84.4482W	1160	RSN
SDS	9.9342N	83.8862W	2340	RSN
URS	9.8350N	83.7782W	1500	RSN
URS0	9.8350N	83.7782W	1500	RSN
BUS	9.5553N	83.7583W	3487	RSN
BUS0	9.5553N	83.7583W	3487	RSN
SJS	9.9392N	84.0542W	1196	RSN
SJS0	9.9392N	84.0542W	1196	RSN
SJSV	9.9392N	84.0542W	1196	RSN
A10	10.4612N	84.7155W	830	RSN
AR1	10.4587N	84.7322W	595	RSN
AR2	10.5613N	84.8933W	763	RSN
AR3	10.5870N	85.0350W	760	RSN
AR4	10.3583N	84.9928W	600	RSN
AR5	10.3413N	84.8247W	1420	RSN
AR7	9.8503N	85.1163W	582	RSN
AR8	10.1925N	85.5205W	511	RSN
AR9	10.4717N	84.7287W	658	RSN
SPS	10.0775N	84.2512W	1120	RSN
CSC	10.0160N	83.9502W	1900	RSN
CUP	10.6633N	85.1500W	500	RSN

LIM	10.6692N	85.2667W	450	RSN
MOG	10.7500N	85.2417W	520	RSN
CRZ	10.9533N	85.5967W	325	RSN
CRZ0	10.9533N	85.5967W	325	RSN
LCR2	9.7422N	84.0030W	1730	RSN
TRT	10.5753N	83.7135W	105	RSN
QCR	9.4198N	84.1653W	45	RSN
QCR0	9.4198N	84.1653W	45	RSN
ACH	8.6635N	79.9292W	900	PANAMA
ARM	8.2832N	82.8665W	10	PANAMA
AZU	7.7917N	80.2740W	14	PANAMA
BRU	8.8068N	82.5608W	3425	PANAMA
BYN	9.1910N	78.8750W	0	PANAMA
DVD	8.4358N	82.4506W	20	PANAMA
ECO	9.3638N	79.6937W	468	PANAMA
FTA	8.6815N	82.2647W	629	PANAMA
IPE	8.9772N	78.4933W	0	PANAMA
LGT	9.0745N	79.9150W	0	PANAMA
UPA	8.9815N	79.5340W	41	PANAMA
BHP	8.9608N	79.5580W	36	PANAMA
CNI	9.4167N	82.5168W	20	PANAMA
BCA	9.4167N	82.5168W	20	PANAMA
ACY	11.9977N	85.2252W	400	NICARAGUA
CNGN	12.5000N	86.6985W	515	NICARAGUA
COS	12.9580N	87.5752W	500	NICARAGUA
CRIN	12.6962N	87.0315W	685	NICARAGUA
CRU	11.9937N	86.3077W	930	NICARAGUA
LEON	12.4160N	86.8925W	158	NICARAGUA
MASJ	11.9873N	86.1513W	440	NICARAGUA
MCH	11.8747N	86.5287W	147	NICARAGUA
MGA	12.1468N	86.2472W	80	NICARAGUA
MIRN	12.4400N	86.7117W	280	NICARAGUA
MOBN	11.8317N	85.9777W	1200	NICARAGUA
MOMJ	12.4083N	86.5400W	500	NICARAGUA
MOYN	11.5357N	85.6958W	50	NICARAGUA
PYN	12.3822N	87.0223W	50	NICARAGUA
PYT	12.5377N	86.0577W	460	NICARAGUA
SSN	11.2878N	85.8495W	415	NICARAGUA
TELN	12.6042N	86.8313W	850	NICARAGUA
TEL3	12.5722N	86.8448W	300	NICARAGUA
MAS	12.0028N	86.1490W	150	NICARAGUA
MASN	12.0028N	86.1490W	150	NICARAGUA
COP	12.1800N	86.5917W	150	NICARAGUA
COP*	12.1800N	86.5917W	150	NICARAGUA
BOA	12.4818N	85.7178W	550	NICARAGUA
BOAN	12.4818N	85.7178W	550	NICARAGUA
SAB*	12.3898N	86.6662W	135	NICARAGUA
MAL*	12.5973N	86.6592W	110	NICARAGUA
ESP*	12.5805N	86.5180W	90	NICARAGUA
AMI*	12.3700N	86.7727W	90	NICARAGUA
PAL*	12.5007N	86.7933W	220	NICARAGUA
JIC*	12.7205N	86.3990W	150	NICARAGUA
LIM*	12.6950N	86.7192W	50	NICARAGUA
SOC*	12.2677N	86.8038W	11	NICARAGUA
PIL*	12.5205N	86.5945W	95	NICARAGUA
CRI2	12.6675N	86.9775W	500	NICARAGUA
XAVN	12.1487N	86.3263W	160	NICARAGUA
CONN	11.5642N	85.6257W	250	NICARAGUA
SOMN	13.4203N	86.6138W	1200	NICARAGUA
APY	12.2277N	86.3528W	260	NICARAGUA
ASE	12.4747N	87.1903W	11	NICARAGUA
QUIN	13.1250N	86.4167W	1605	NICARAGUA
RTN	12.5333N	86.7832W	240	NICARAGUA
CNR	12.6725N	87.0722W	240	NICARAGUA

model and RSN 1D model (step 2, Figure 5). In this third step of our procedure, a mix of the two good 1D models from step 2 is used as first-guess initial velocity model, again followed by subsequent inversion testing various initial velocity models of different layer thicknesses and different velocities. The final result of this step is a preliminary minimum 1D model with station delays for Costa Rica (Figure 6). The data used in this step is incomplete, possibly inconsistent, and likely many events are listed twice. This preliminary minimum 1D model with appropriate station delays is preferred over the original OVSICORI-UNA and RSN models (Figure 4), since it guarantees a uniform (high) location quality and uniform phase identification for the two networks.

In the fourth step, all 10350 events (1984-1997) from OVSICORI-UNA and 3510 events (1992-1998) from RSN are relocated using the preliminary minimum 1D model with station delays and a constant Vp/Vs ratio of 1.78 (Quintero and Kulhanek, 1998) to calculate the corresponding S-wave velocities.

The fifth step in the merging process (Figure 5) concerns the recognition of events from the period 1992 to 1997 that occurred in both data sets and that may be recognized by their similar hypocentral parameters (“check for event pairs”, see Figure 5). We apply two sets of correlation criteria:

(1) If two origin times fall in a time window of 10 sec and the epicentral and depth differences are less than 30 km, we term it a very likely event pair.

(2) If two origin times fall in a time window of 20 sec, the epicentral difference does not exceed 160 km, and the depth difference is less than 200 km, we call it a possible event pair.

The first group consists of 1116 event pairs with average differences in origin time, hypocentral depths, and epicenter location of 0.32 sec, 7.4 km, and 7.8 km, respectively. These differences in hypocenter parameters are the result of (mainly) randomly distributed observation errors and possible clock errors in combination with the particular station configuration. It may be considered an optimistic estimate for the average location error achievable by each individual network. With the merged data set a higher location precision is very likely, since the station configuration for the com-

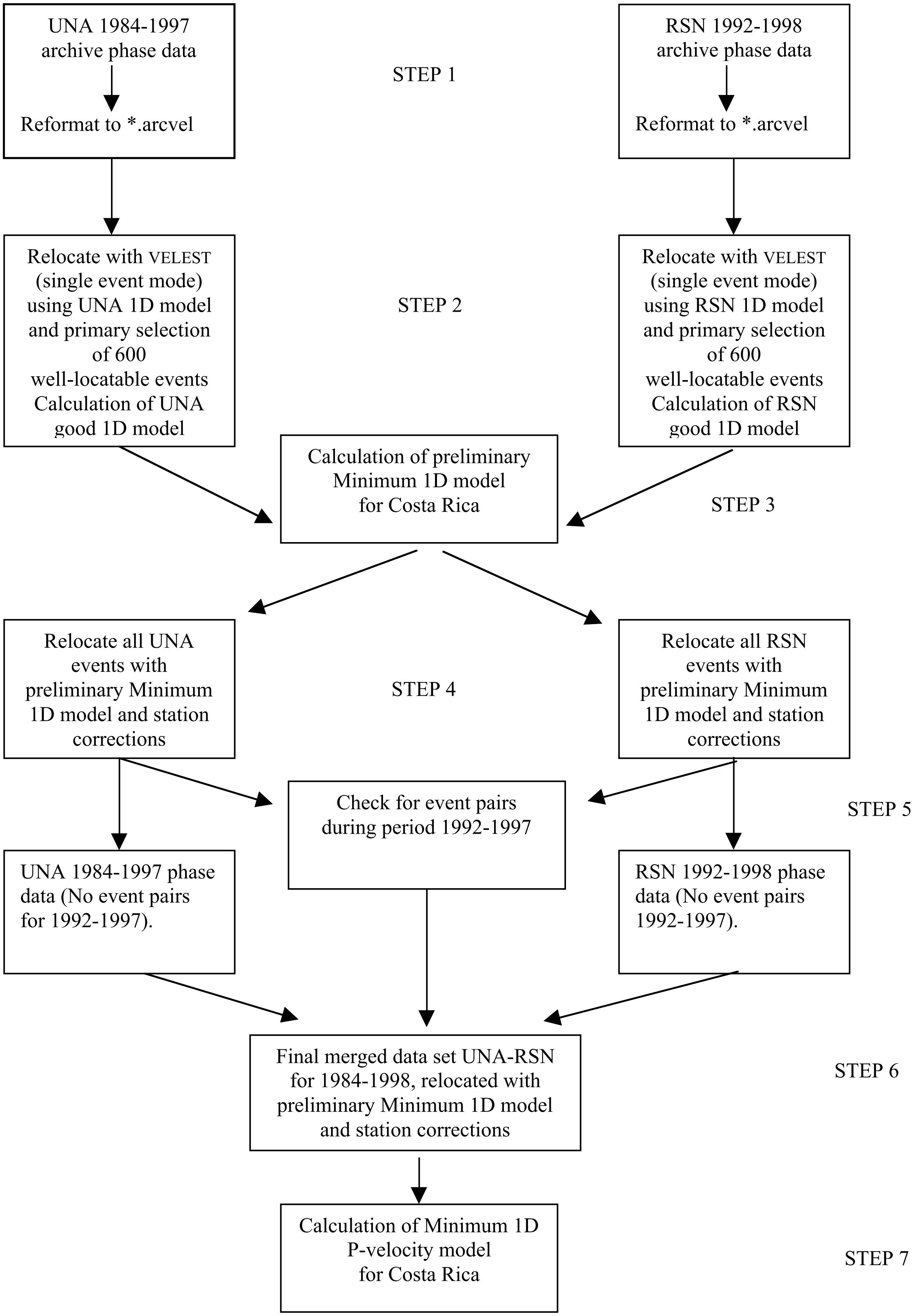

Fig. 5. Overview of procedure to merge local earthquake data sets from OVSICORI-UNA and from RSN station network and to calculate minimum 1D model for Costa Rica (see text for details).

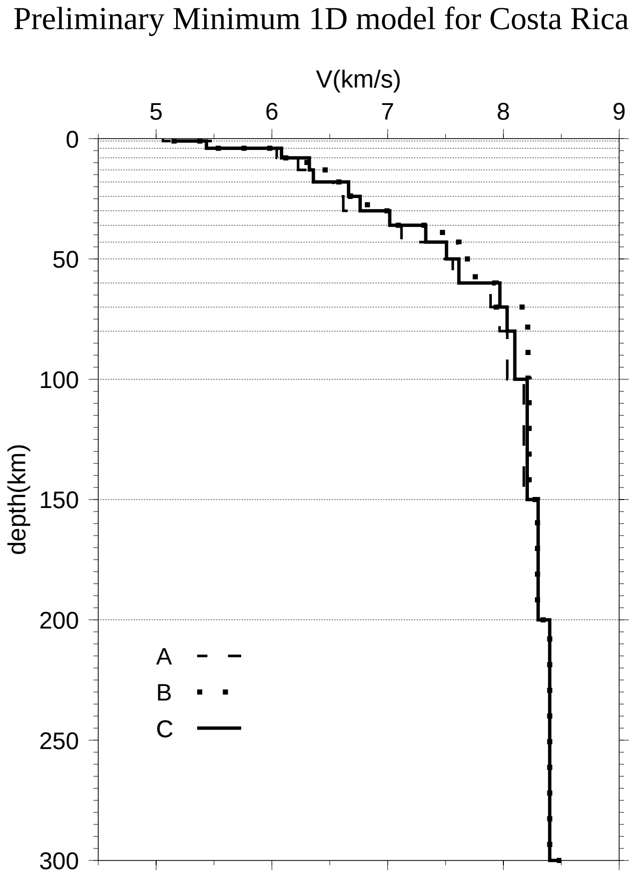
Preliminary Minimum 1D model for Costa Rica

Fig. 6. P-wave velocity models for Costa Rica calculated by simultaneous inversions of hypocentral and model parameters (steps 2 and 3) and used during the merging process (see Figure 5 and text). A: Good 1D model for OVSICORI-UNA network; B: Good 1D model for RSN network; C: Preliminary minimum 1D model for Costa Rica.

bined networks is favorable, unless systematic errors were introduced during the merging process. Large errors mainly originate from assigning observations from two different events to one single event. Hence, special care is taken when identifying event pairs to check for other possible correspondences. Most triple-event correspondences, however, are caused by double reports of the same earthquake in the original data sets. After deleting all questionable correspondences, 1096 event pairs in the first group remain (see Figure 7a).

The second group contains 206 possible event pairs, some of which contain one event already paired in the first group. The majority of the possible event pairs needed checking by comparing arrival times at stations that are situated very close to each other but belong to different networks. Fortunately, there exist several such “station pairs” in Costa Rica, thus allowing us to safely identify 190 event pairs in the second group (Figure 7b). On average, the differences in origin time for these event pairs are 1.85 sec, in epicentral distance 57 km, and in hypocentral depth 32 km.

After merging the phase data from 1286 event pairs, the single-report events from OVSICORI-UNA and RSN are appended to compile a complete data set for the period 1992 to 1997. The complete data set for Costa Rica for the period 1984 to 1998 (step 6, see Figure 5) consists of 11 848 events with 132 331 P-wave and 86 018 S-wave observations. Since the stations of the two networks in Costa Rica are mostly equipped with vertical-component seismometers only, S-wave observations are less reliable than P-wave observations. S-wave observations have not been used in the location and merging process and are simply appended to the event data as valuable additional information. This concludes the merging process and we now may treat this data set as it were observed by a single network. We proceed (step 7, see Figure 5) with the routine procedure of calculating a minimum 1D P-wave velocity model with station delays (Kissling *et al.,* 1994).

CALCULATION OF A MINIMUM 1D MODEL FOR COSTA RICA

From the complete (merged) data set for Costa Rica from 1984 to 1998 relocated with the preliminary minimum 1D model (step 6, Figure 5), we select the best data for calculating a minimum 1D P-velocity model for Costa Rica, i.e., those events with a gap (largest angle between two neighboring stations as seen from the epicenter) ≤160º that are potentially well-locatable and that are reported by a large number of stations (applied selection criteria: 12 or more P-wave observations). These criteria lead to a data set of 843 events. Joint hypocenter determination calculation of several hundred events with VELEST is a valuable tool to identify errors in large travel time data sets (Kissling 1988). By comparison with observations from (apparently) nearby events, we identified several event data sets that contained a single, few, or many observations of more than 2 sec readings errors. While the first two cases denote errors in the original data sets, the latter cases likely result from erroneously merging the data from two different events. Since the two networks OVSICORI-UNA and RSN largely overlap and since we only selected events within the combined station network, the ultimate cause of errors of the merging process are again in the original data sets. Without access to the original seismic signals, correction of these large errors in the travel time data is impossible and, consequently, these events were rejected. The final travel time data set used for the calculation of the minimum 1D model consists of 822 well-locatable events with 14 774 P observation at 89 stations.

The appropriate layering of the 1D model is found by a trial-and-error process. We start with the velocity-depth function of the preliminary minimum 1D model (result of step 3 of the merging process, see Figure 5) using an arbitrary layer thickness of 2 km for shallow crustal levels and increasing layer thickness with depth to about 4 to 5 km at

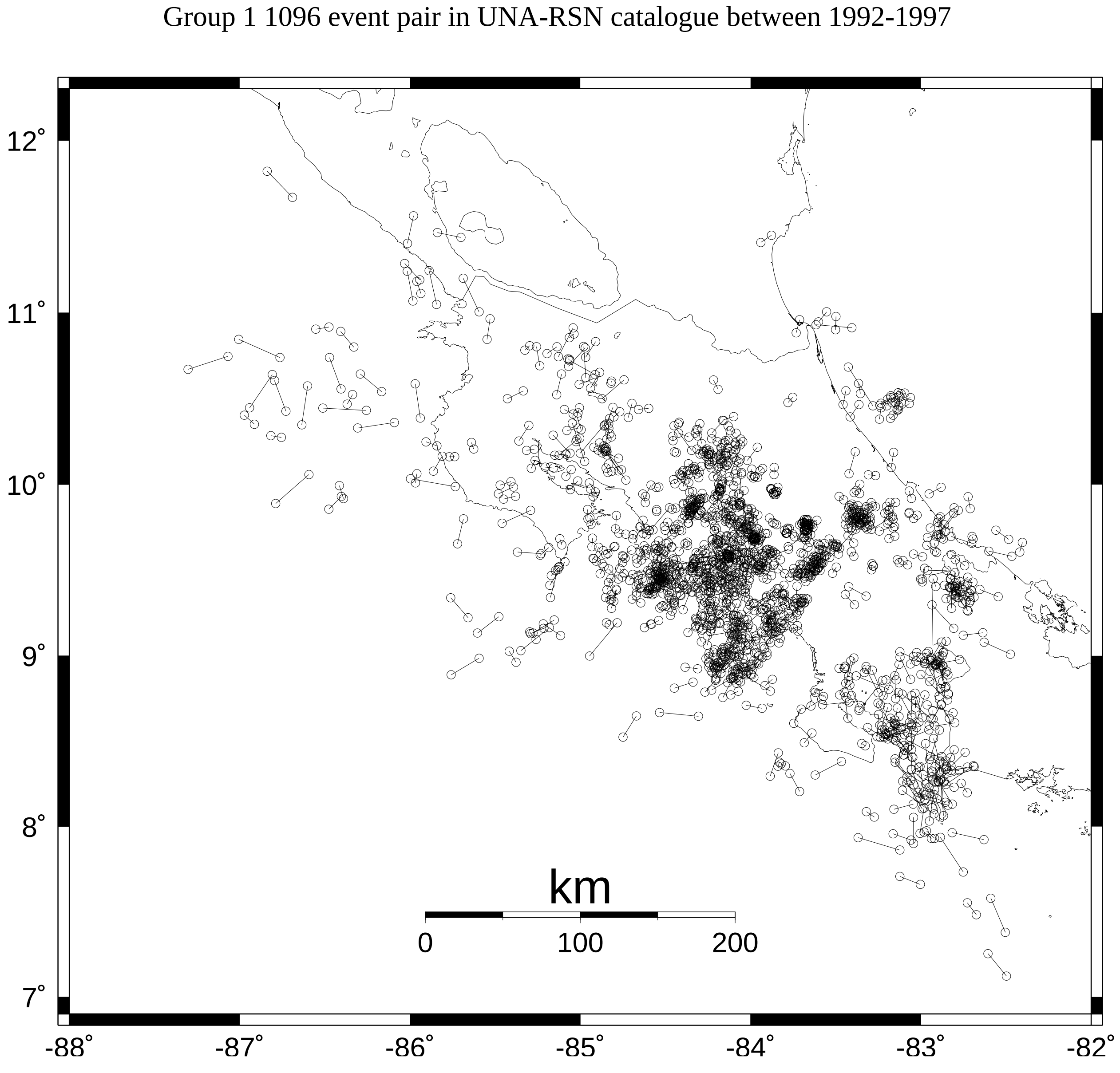

Fig. 7. Epicenter pairs recorded separately by OVSICORI-UNA and RSN networks but belonging very likely (Figure 7a) and possibly (Figure 7b) to same seismic event. The epicenter pairs are joined by a line while each circle indicates an epicenter.

Moho and to 10 km below 60 km depth. The station OCM is selected as reference station for Costa Rica and we test different sets of layers in the input velocity model representing the near-surface structure, since the topmost station is about 3500 m above sea level. The resulting solutions were almost identical; therefore we decide to use the simplest near-surface model with the top velocity layer ranging from 4 km above to 1km below the sea level, thus encompassing station topography. In subsequent inversions, various initial velocity models of different layer thicknesses and different velocities are tested for their performance. This probing of the solution space clearly documented the need to represent the average velocity-depth function beneath Costa Rica with a series of relatively thin crustal layers thus mimicking a velocity gradient rather than distinctive velocity layering.

Figure 8 shows the final minimum 1D P-velocity model with station delays for Costa Rica and the hypocenters employed for its calculation. Using this model with station corrections, the average RMS-error for the 822 events is further reduced from 0.43 sec with the preliminary minimum 1D model to a final value of 0.31 sec. This denotes an overall reduction in RMS of 50% with respect to the average RMS value for the same data set achieved by using OVSICORI-UNA and RSN original location models. Unfortunately, absolute mislocation errors for the combined OVSICORI-

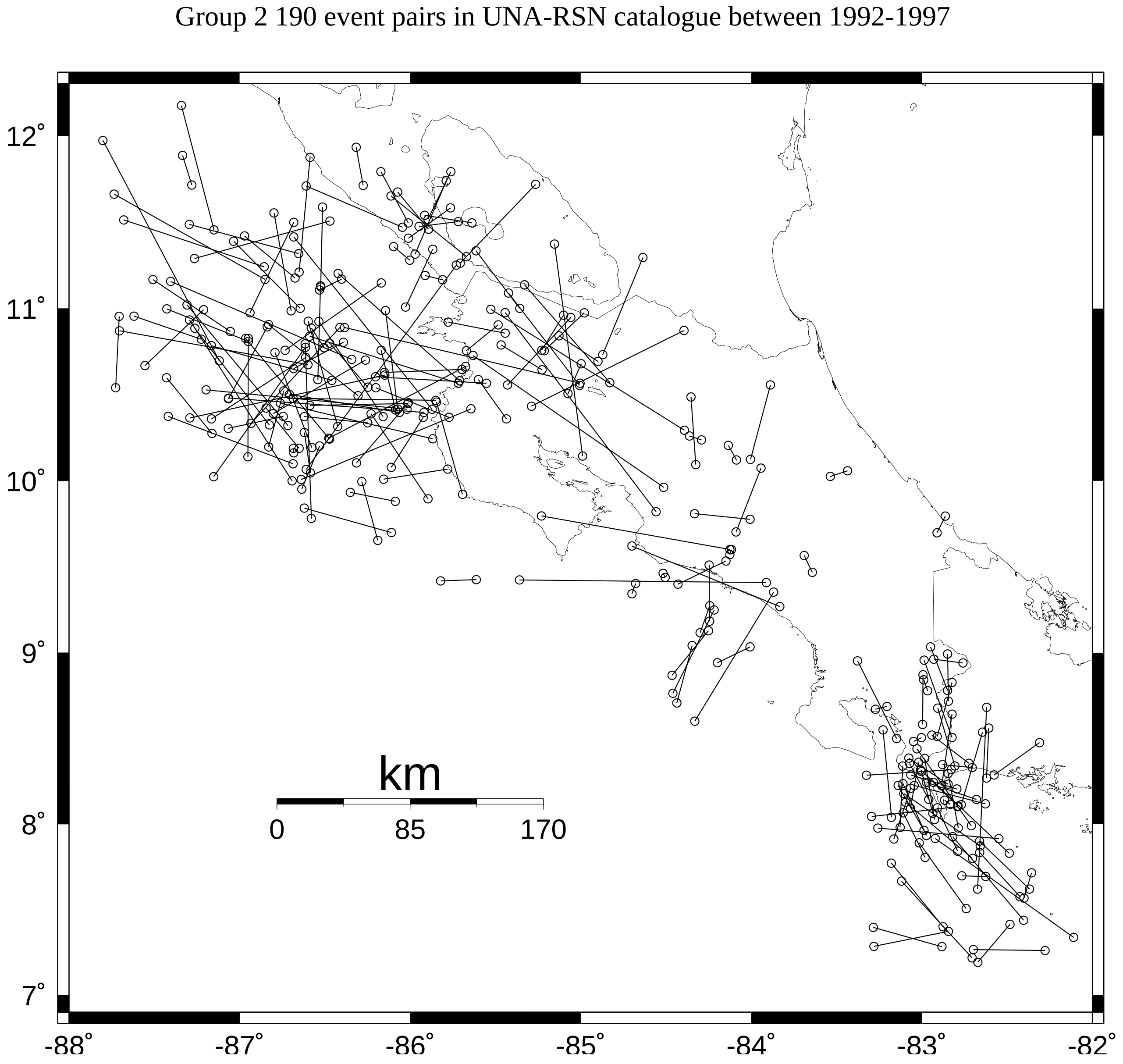

Fig.7b. See last figure.

UNA and RSN networks when using the minimum 1D model for Costa Rica cannot be calculated due to lack of quarry blast data. Comparison with similar networks and data (e.g., Kissling *et al.,* 1995b; Haslinger *et al.,* 1999; Husen *et al.,* 1999), however, leads to an estimated mislocation error of 5 km for well-locatable events.

In a previous study by Quintero and Kulhánek (1998) the crustal structure in Costa Rica was represented by a crustal layer with P-velocity of 6.56 km/sec, a Moho depth of 34 km, and an upper mantle velocity of 7.79 km/sec. Their model represents a simplified average velocity structure for the top 100 km with respect to the minimum 1D model derived in this study (Figure 8). The most significant difference with previous 1D velocity models for Costa Rica is the rather smooth gradient from 6 km/sec to 7.3 km/sec in the crust and a wide transition zone encompassing the Moho and leading to mantle velocities. This is the result of averaging over regions of different crustal thickness and of a significant number of rays sampling the subducting slab.

Reliability of the resulting 1D velocity model may be estimated by performing a series of inversions with different -even extreme- initial models while applying only weak damping for all unknowns (Kissling *et al.,* 1995a). The results of these tests for our case document fast convergence to a

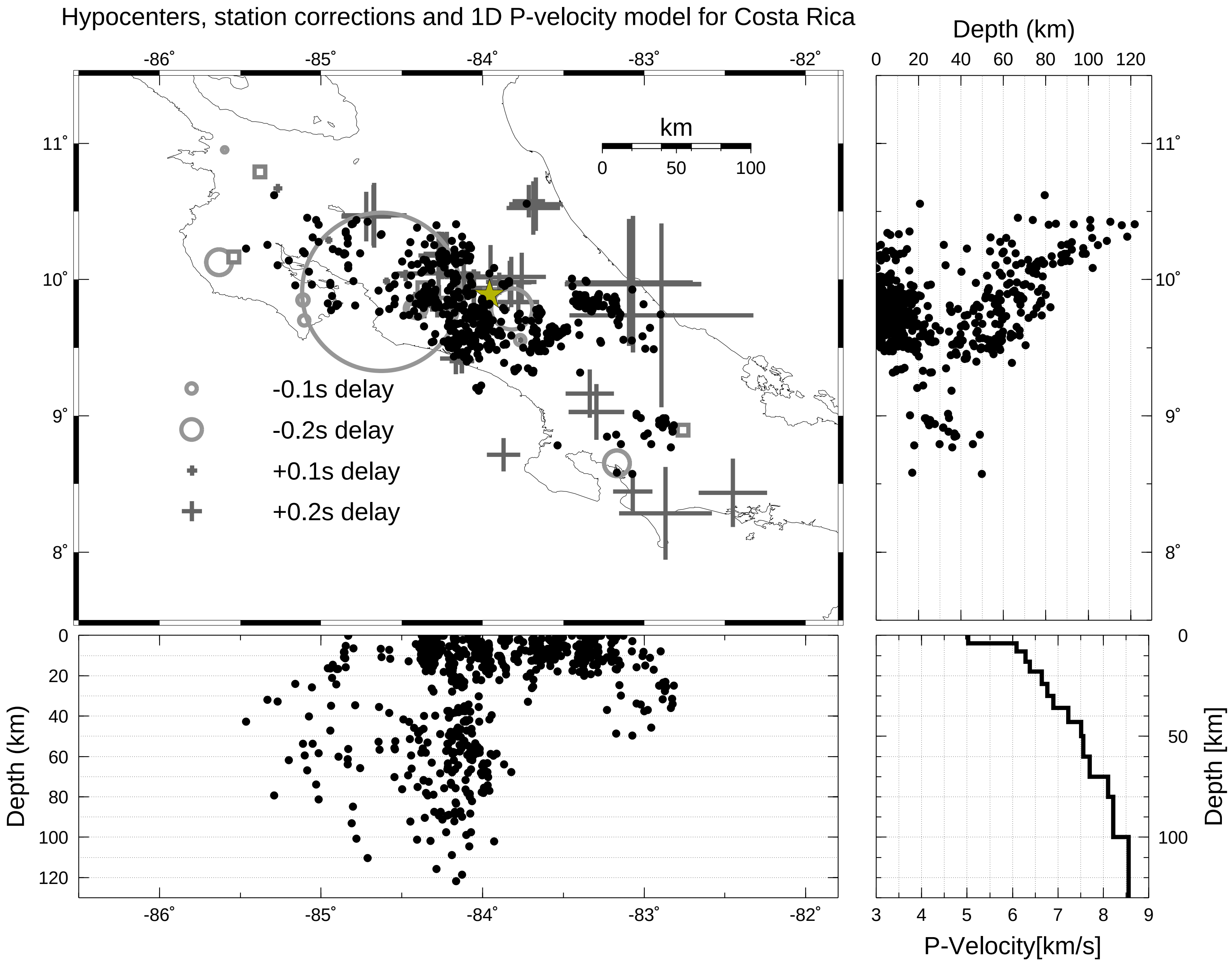

Fig. 8. Minimum 1D P-velocity model for Costa Rica with station delays. A star marks the reference station (OCM). Crosses and open circles show the station delays relative to the reference station. Stations with delays smaller than +/-0.05 sec are represented by open squares. EW and NS cross sections show distribution of 822 hypocenters used in simultaneous inversion for hypocentral and model parameters.

stable solution. Results of two tests are displayed in Figure 9 representing an initial velocity model of low crustal velocities and of a very pronounced Moho discontinuity at 40 km depth ("low velocity input") and a second initial velocity model of rather high crustal velocity with no Moho discontinuity at all ("high velocity input"). For both initial models (and using zero station delays on input) resulting velocity models correspond to within 0.05 km/sec with each other and with the minimum 1D model with the exception of the top layers. Due to unfavorable ray coverage -mostly subvertical for the top layers- resulting velocities more strongly depend on initial values leading to differences in velocities of 0.1 km/sec for layer one, 0.3 km/sec for layer two, and of 0.2 km/sec for layer three.

The shallow subsurface of Costa Rica is characterized by strong lateral velocity variations due to different lithologies varying from sedimentary layers of volcanic ash to former oceanic crustal rock formations (Weyl 1980; Escalante 1990; Denyer and Kussmaul 1994). These variations should be accounted for, at least in parts, by the station delays obtained simultaneously with the velocities of the minimum 1D model. For stations with a homogeneous azimuthal ray distribution, i.e., toward the center of the network, station corrections will reflect the near-surface lithology (Haslinger *et al.*, 1999). Due to mostly long ray paths and limited azimuthal ray coverage, station corrections in the outer regions of the network contain velocity information of the shallow subsurface and linear effects of the deep structure. In our minimum 1D model for Costa Rica (Figures 8 and 10), stations situated on the Limon and Bocas del Toro Basins show delayed P-arrivals. Delayed P-arrivals are also observed at stations in southeastern Costa Rica, where the low near-surface velocities of the Terraba and Chiriqui Sedimentary Basins provide the likely cause. The central part of Costa Rica is also characterized by delayed arrivals (see Figure 10). The

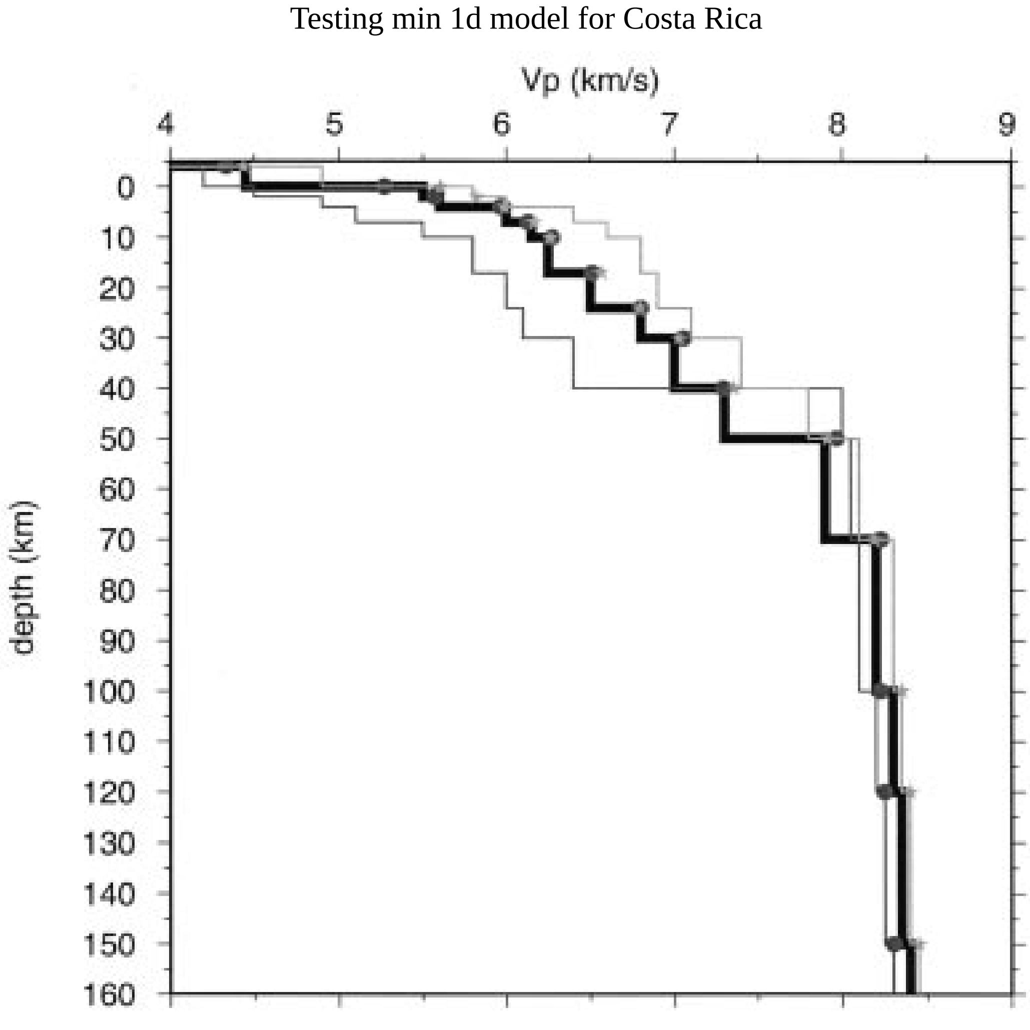

Fig. 9. Stability testing of the minimum 1D P-wave velocity model for Costa Rica. The thick solid black line denotes the minimum 1D model. The two thinner lines represent the low- and the high-velocity initial models, respectively. The dots show the resulting velocities after 7 iterations for the low-velocity initial model and the stars mark the resulting velocities after 6 iterations for the high-velocity initial model. The two tests clearly document rapid convergence and stability of the derived minimum 1D P-wave velocity model for Costa Rica.

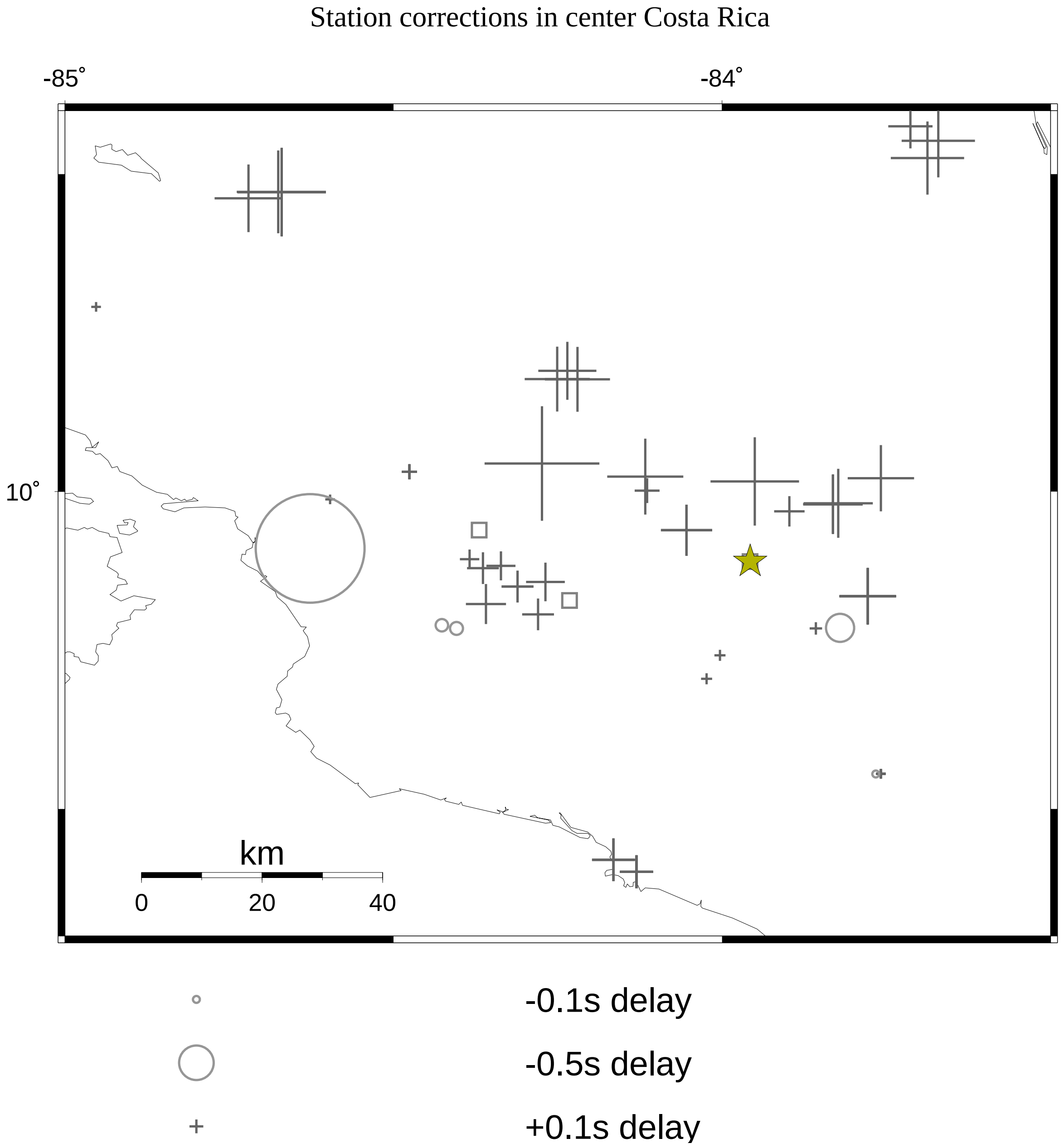

Fig. 10. Station delays of minimum 1D model for central Costa Rica (detail from Figure 8). Crosses and open circles denote station delays relative to the reference station OCM marked by a star.

probable cause of this delay is associated with the velocity structure of the volcanoes since many stations in this region (IRZ2, ICR, VTU, POA2, VPS2, VACR, and FOR) are situated at or near the top of volcanoes. Finally, the western part of Costa Rica in the Nicoya Peninsula shows early P-wave arrivals (negative station delays). Possibly this is caused by the predominantly updip travelling waves originating from deeper events within the high-velocity subducting slab, as suggested by similar results obtained for the northern Chilean subduction zone by Husen *et al.,* 1999. Overall, these station delays are clear indicators of strong lateral velocity variations in the near-surface but also likely throughout the crust.

DISTRIBUTION OF HYPOCENTERS 1984 TO 1998 IN COSTA RICA

We use the minimum 1D P-velocity model and station corrections to relocate all events. Figure 11 shows the hypocenter distribution recorded between 1984-1998 within the study area for well-locatable events.

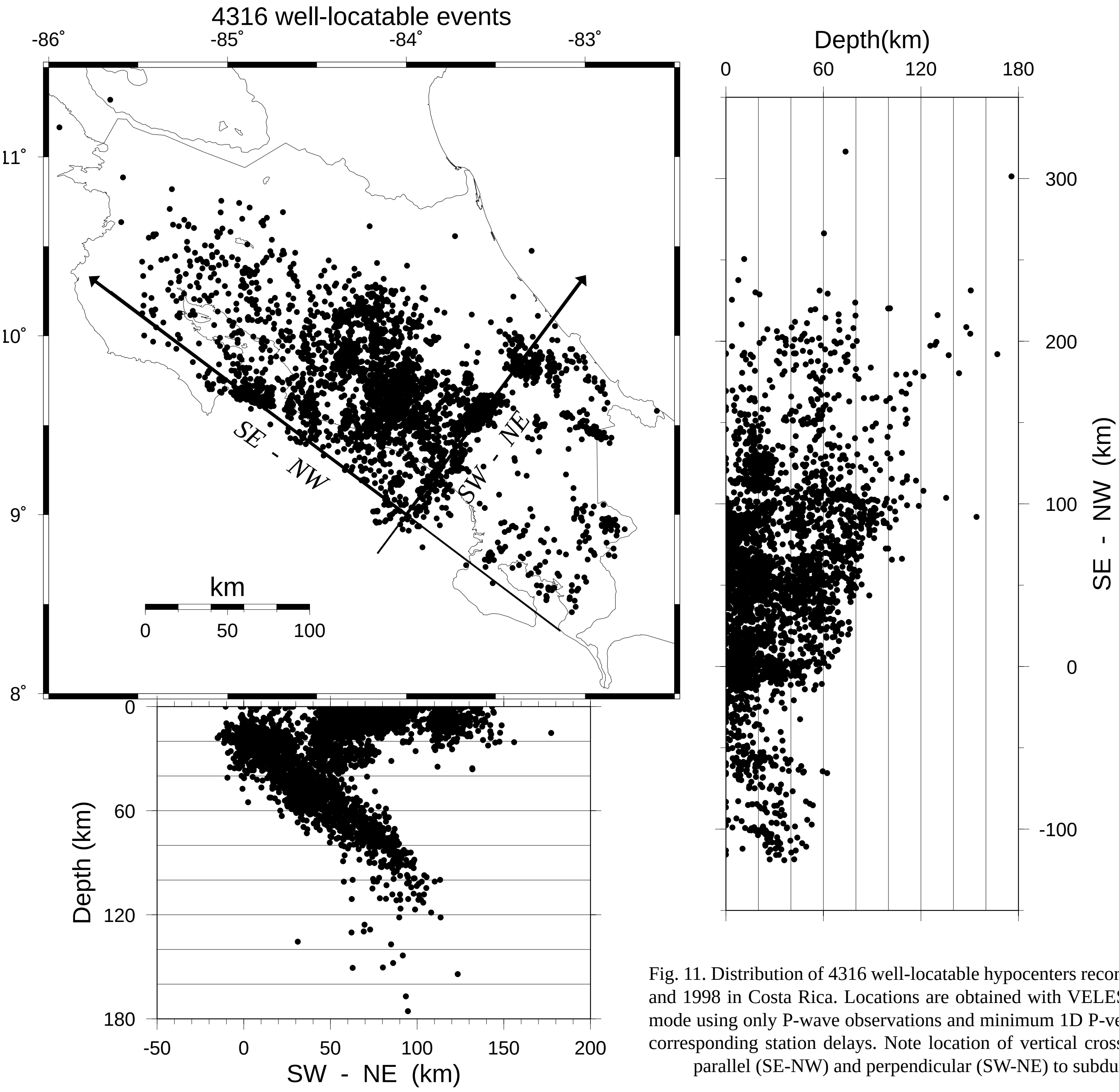

Fig. 11. Distribution of 4316 well-locatable hypocenters recorded between 1984 and 1998 in Costa Rica. Locations are obtained with VELEST in single-event mode using only P-wave observations and minimum 1D P-velocity model with corresponding station delays. Note location of vertical cross sections running parallel (SE-NW) and perpendicular (SW-NE) to subduction trench.

In general the hypocenter distribution (Figure 11) is similar to findings of previous studies (e.g., Protti *et al.,* 1995). Figures 8 and 11 document seismogenic regions with surprisingly different depth ranges at either side of a sharp boundary striking approximately SW-NE from a point near 9°N/ 83.7°W. The hypocentral depths for events outside the combined station network of Costa Rica and, in particular, the hypocenters within the Cocos plate at the border region between Costa Rica and Nicaragua are poorly constrained. Southeast of the above-mentioned boundary, a moderate seismic activity is confined to the top 40 km. Northwest of the boundary, two regions of high seismic activity are observed: The Benioff-Wadati zone of about 45 km width descending at an angle of 45 degrees, and the seismic activity mainly within the crust of the overriding plate.

CONCLUSIONS

The merging of local earthquake travel time data sets reported by the two seismic networks OVSICORI-UNA and RSN results in a data set for Costa Rica for the period 1984 to 1998 consisting of 11 848 events with 13 2331 P-wave and 86 018 S-wave observations. With 4316 well-locatable events (Figure 11) this constitutes a prime data set for future local earthquake seismic tomography studies. Consistency and quality of the P-wave observations have been given the first priority during the merging process. Hence, this data set may not be complete. Stations of the two networks are mostly equipped with vertical-component seismometers only. S-wave observations, therefore, have not been used in the merging process and are appended to the event data as valuable additional information.

Successful merging of two local earthquake data sets relies on accurate hypocenter locations (Solarino *et al.,* 1997). Overall quality and consistency of a merged data set primarily depend on a correct, updated, and complete station list and on the velocity models used for routine earthquake location. The first requirement is met by the "master station list" (Table 1) for Costa Rica and the second by the preliminary and final minimum 1D P-velocity models. The compilation of the master stations in this study documents several small problems with the information about seismic stations of the various seismological networks in Central America that can lead to significant errors in event location and certainly leads to wrong error estimates. Such location errors may not be detected during single-event location procedures but they become more obvious when joint hypocenter determination routines such as VELEST are applied.

The minimum 1D P-velocity model for Costa Rica allows locating earthquakes within the combined seismic station network of OVSICORI-UNA and RSN with uniform high accuracy. In addition, the usage of this velocity model for routine hypocenter location improves consistency in phase identifications. The station delays obtained with the minimum 1D P-velocity model indicate strong lateral velocity variations in the near-surface and probably throughout the crust and, in general, correlate well with surface geology. Thus, the station delays demonstrate the need for using a minimum 1D model for high-precision earthquake location (Kissling *et al.,* 1994) but also document the potential and the need for seismic tomography applications (Yao *et al.,*1999; Sallares, 1999) with a consistent data set.

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Ronnie Quintero[1,2] and Edi Kissling[3]

[1] Universidad Nacional de Costa Rica, Costa Rica
Email: rquinter@samara.unam.ac.cr
[2] Department of Earth Sciences, Uppsala University, Sweden
[3] Institute of Geophysics, ETH Zürich, Switzerland