Crustal model for Hispaniola

Jens Havskov (1) and Javier Rodríguez (2)

1) Department of Geoscience, University of Bergen, Norway
2) Observatorio Sismológico Politécnico Loyola, San Cristóbal, Dominican Republic

Abstract

A new crustal model for Hispaniola has been determined with data from the Loyola seismic network and cooperating stations. The model has been determined by locating selected events using a large number of models in a systematic grid and selecting the model with the lowest average *rms* travel time residual. The model found is:

P-velocity (km/s)	Depth to interface (km)
5.5	0.0
6.3	10.0
6.7	22.0
7.7	36.0
8.0	44.0

with Vp/Vs=1.75. The model is shown to give a significant improvement in locations, particularly for the hypocentral depth as well as giving lower *rms*. The model is only an approximation of the strong 3D structure, but a best approximation for locating earthquakes in 1D with the test data set.

Introduction

The seismic model for earthquake location for Hispaniola used by the Observatorio Sismológico Politécnico Loyola (OSPL) has for a long time been the default model supplied with SEISAN (Havskov et al. 2020) used for the routine processing at OSPL. After 11 years of operation, the network has increased from 3 stations to 15 (https://www.fdsn.org/networks/detail/LO/) and the network in addition use 18 other publicly available stations. There is thus now data from many recordings making it possible to try to develop a new model. So, an attempt will be made to make a new model appropriate for earthquake location for the whole island.

Existing models

The model used routinely has been the Norwegian model that comes with SEISAN (Table 1).

Table 1. The model used now. Vp is the P-velocity.

Vp (km/s)	Depth to interface (km)
6.2	0.0
6.6	12.0
7.1	23.0
8.05	31,0
8.25	50.0
8.5	80.0

Vp/Vs=1.74. Distance weight is 1.0 until 1100 km and decreases to 0.0 at 2200 km. For the southern part of the country, a new model was made in connection with a local study (Rodríguez et al., 2018) where data until 2016 was used.

Table 2. P velocity for the model used in Rodríguez et al. (2018). Vp/Vs =1.80.

Depth to interface (km)	P-velocity(km/s)
0.0	5.3
4.0	5.4
6.0	5.8
9.0	6.5
20.0	7.0
25.0	7.7
40.0	8.1
220.0	8.5

That model was based on a few published models. In subsequent routine operation of the network, the new model was tested but did not seem appropriate for the whole country, so the original Norwegian model has been used until now.

The national network uses the model in Table 3, (Jottin Leonel, personal communication), where Vp/Vs= 1.76. Distance weight is 1.0 until 1100 km and decreases to 0.0 at 2200 km.

Table 3. Velocity model used by the national network (SDD).

Vp velocity (km/s)	Depth to interface (km)
4.6	0.0
5.0	5.0
5.4	10.0
5.7	15.0
6.0	20.0
6.8	30.0
7.49	40.0
8.05	80.0
8.63	

In addition, there is a large study of the crustal structure of the Dominican Republic (Núñez et al. 2019) which can give some idea of the structure (Figure 1).

From the Núñez study, it is seen that the crustal structure varies significantly laterally and any 1D model will be a gross approximation, however that is what is needed for earthquake location.

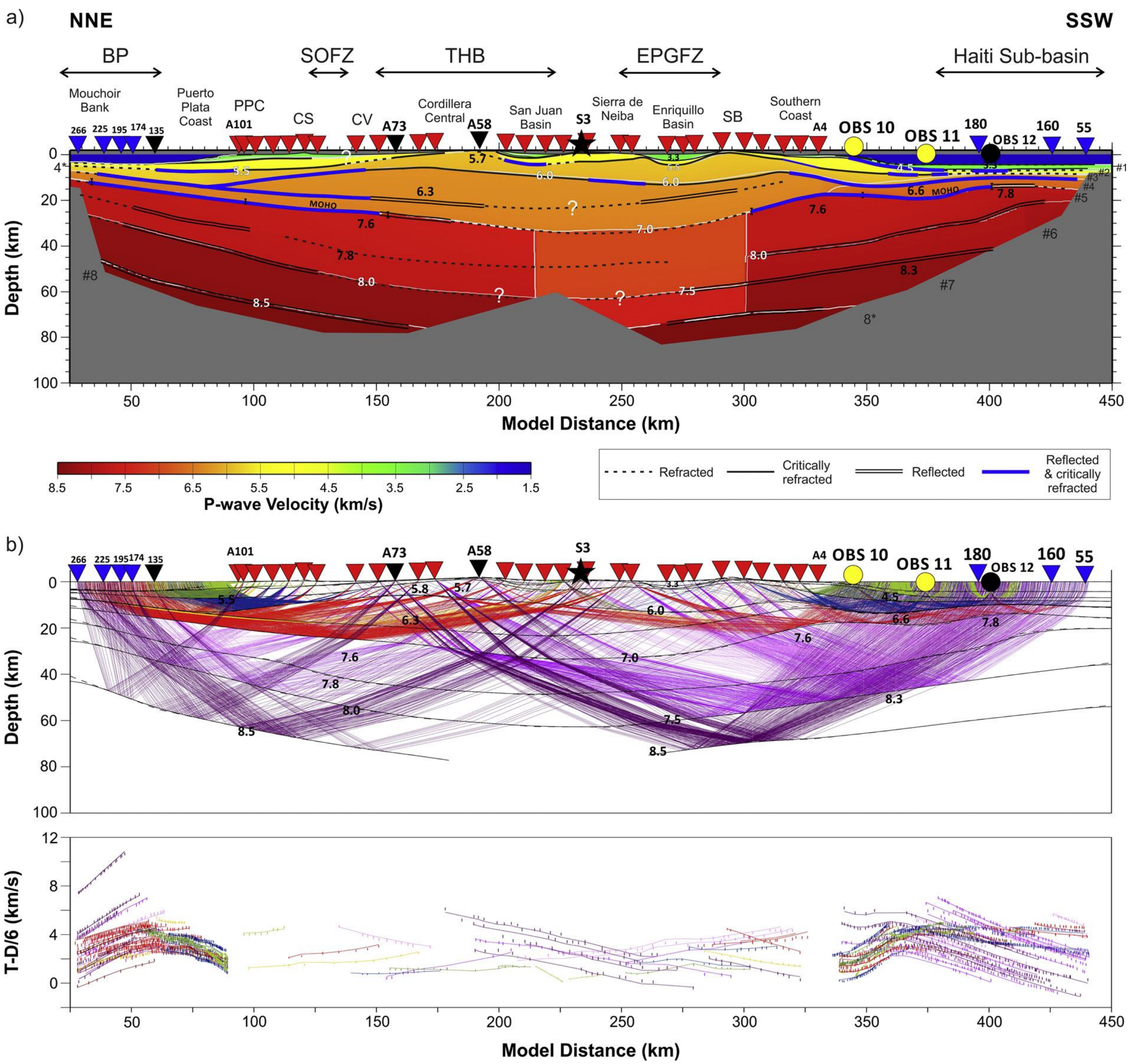


Figure 1. The proposed model for part of Dominican Republic. The profile goes from North to South across the central part of the island. For details, see Núñez et al. (2019).

In our study we will use grid search for the best model. This consists in selecting a data set of well-located events and relocating them using a few thousand models selected in a systematic grid. The model with the lowest average *rms* will then be selected.

Data

For the grid search, data was selected using the following parameters:

Time period: 2018 to 2023 (October)

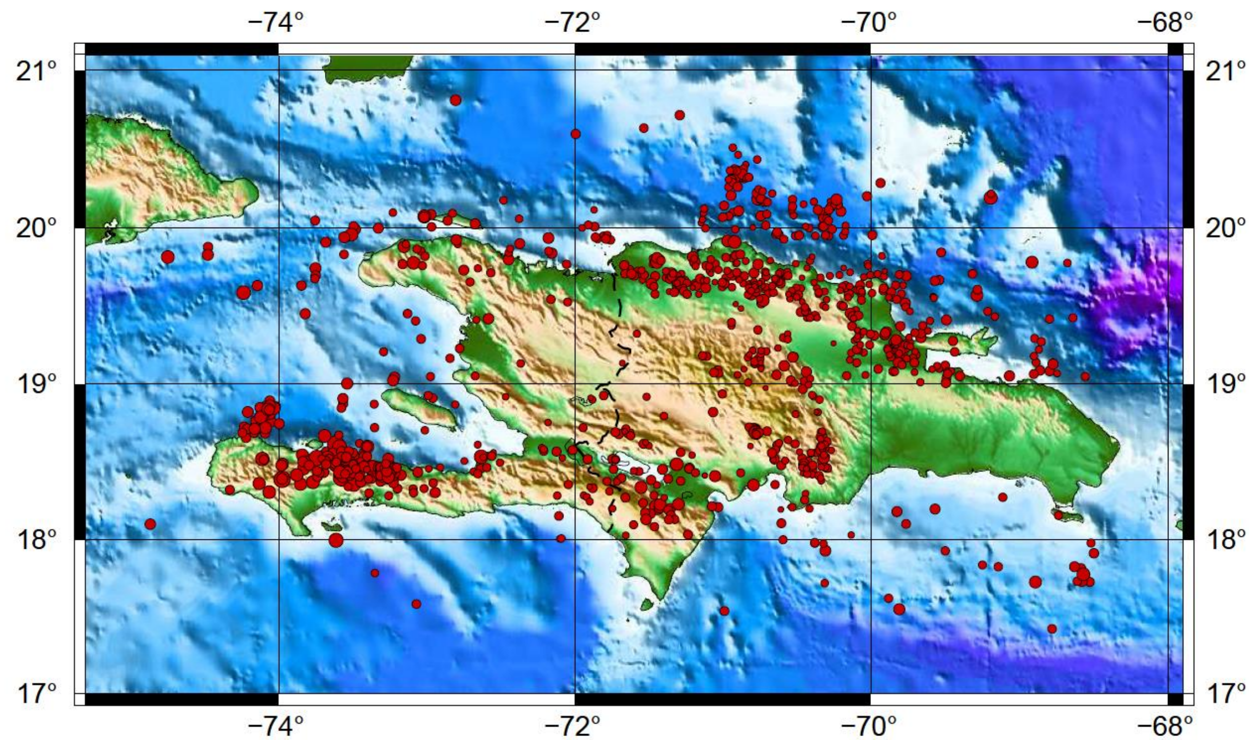
Area: 17-21 deg. North and 75 to 68.5 West

Maximum *rms*: 0.7 s

Maximum depth: 50 km

Minimum number of stations: 10

Shallow events were selected to particularly study the crust. The number of events found was 1,045. The map of the events is seen in Figure 2.



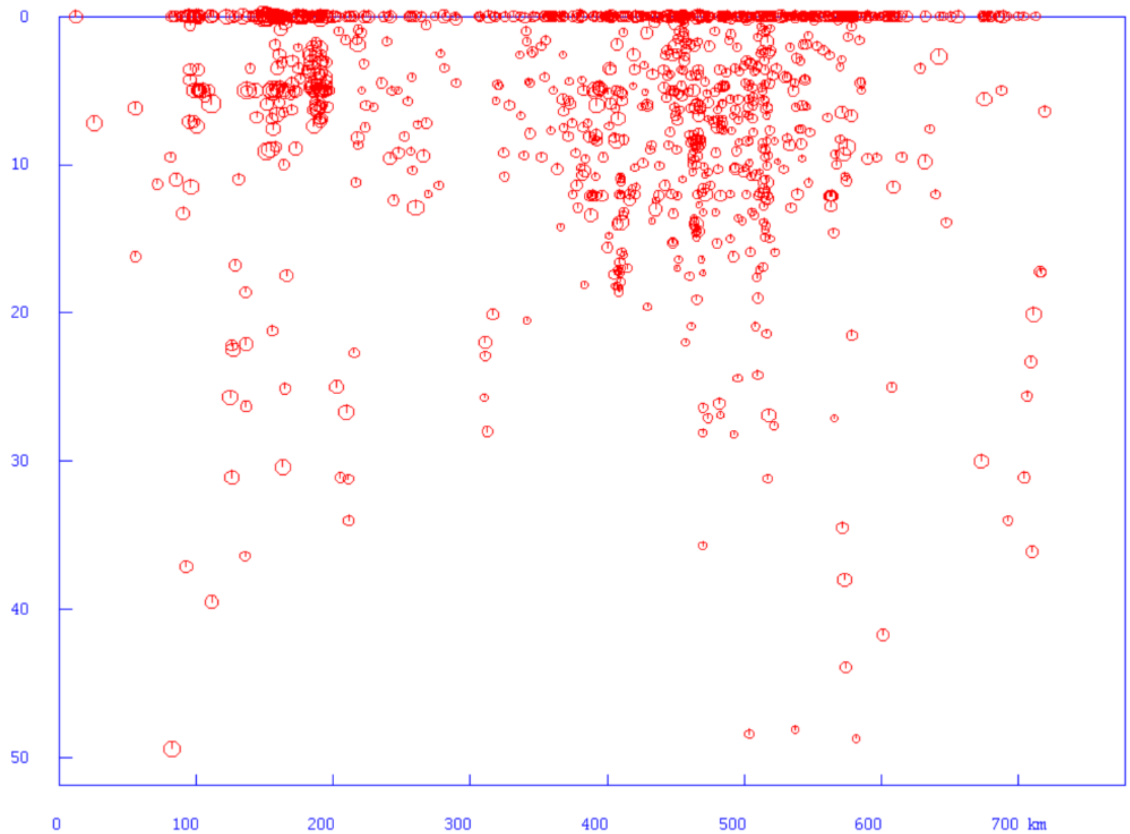


Figure 2. Events selected for the study. Epicenters (top) and EW profile (bottom). The events have not been revised and are taken from the network data base.

It is seen that the events are distributed over most of Hispaniola so they should be reasonably representative of the area. Most of the events are at less than 20 km depth and many are at zero km depth. Zero km depth is an indication that the model is not correct since very few local events are expected to be shallower than 5 km. Several of the events had a fixed depth. The fix-flag was removed for the tests. (Figure 2)

The tests for different models were made with the SEISAN ***hyp*** program which has a special option to vary the velocity in each layer as well as the layer thickness in a systematic way making it possible to test many different models. The Vp/Vs ratio can also be included in the testing.

The tests were made using only data to 200 km distance. Full weight was used up to 100 km and the weight of the arrival times then decreased linearly from 100 km to 200 km. The advantage of using the short distance is that the depths will be more accurate since far stations have less influence.

It turned out that all test events could not be used with 200 km distance due to the events not having enough stations within 200 km distance and only 991 events out of the 1045 were used to determine the model. In the following, only these events will be used. In practice it would however be an advantage to use larger distances so when comparing the new model to the other models, a comparison with distance up to 350 km will also be made. Tests were also made with different Vp/Vs ratios. They all showed that a value of 1.75 gave the lowest *rms*.

Table 4 Comparing different models. Tests are made with the test data set to compare average results. Abbreviations: ORG= Original model used currently, NEW: New model made with data to 200 km distance, SDD: National network model, Av h: the average hypocentral depth (km), VP: P- velocity (km/s), H: depth to interface (km). Distance is the station distance range (km) used for the tests.

	ORG VP H	ORG	ORG	SDD VP H	SDD	NEW VP H	NEW
	6.2 0.0			5.0 0.0		5.5 0.0	
	6.6 12.0			5.4 10.0		6.3 10.0	
	7.1 23.0			5.9 20.0		6.7 22.0	
	8.05 31.0			6.8 30.0		7.7 36.0	
	8.25 50.0			8.05 50.0		8.0 44.0	
Distance	100-200	100-350	1100-2200	100-200	100-350	100-200	100-350
Vp/Vs	1.74			1.76	1.76	1.75	1.75
Rms	0.487	0.579	0.583	0.653	0.842	0.404	0.525
Av h	8.3	5.7	6.1	25.5	28.2	17.3	17.7

Testing many different models will result in many models having almost the same *rms* since increasing the velocity in one layer and decreasing it in another layer might have the same effect on the *rms*. So, all the parameters can play off against each other. For the model found, the *rms* only change by 0.02 s. varying the velocity by 0.4 km in the last 3 layers and the layer thickness by 3-6 km. (Table 4)

The layering as shown in table 4 has been simplified for SDD to make it easier to compare to the other models. However, in the computational tests, the detailed model is used. For each model using data in different distance ranges, the average depth and *rms* has been calculated. The SDD and NEW models are significantly different until 40-50 km depth with the SDD model having smaller values of Vp compared to the NEW model. Compared to the 3D model in Figure 1, it seems that the NEW model is closer to the average 3D model than the SDD model which would explain why the SDD model has larger *rms* than the NEW model.

In general, it is seen that when increasing the distance to which data is used, the *rms* increases due to more data being used. The new model, NEW, has the overall lowest *rms* for all models. When comparing models using the same distance range, the SDD model always has the largest *rms*.

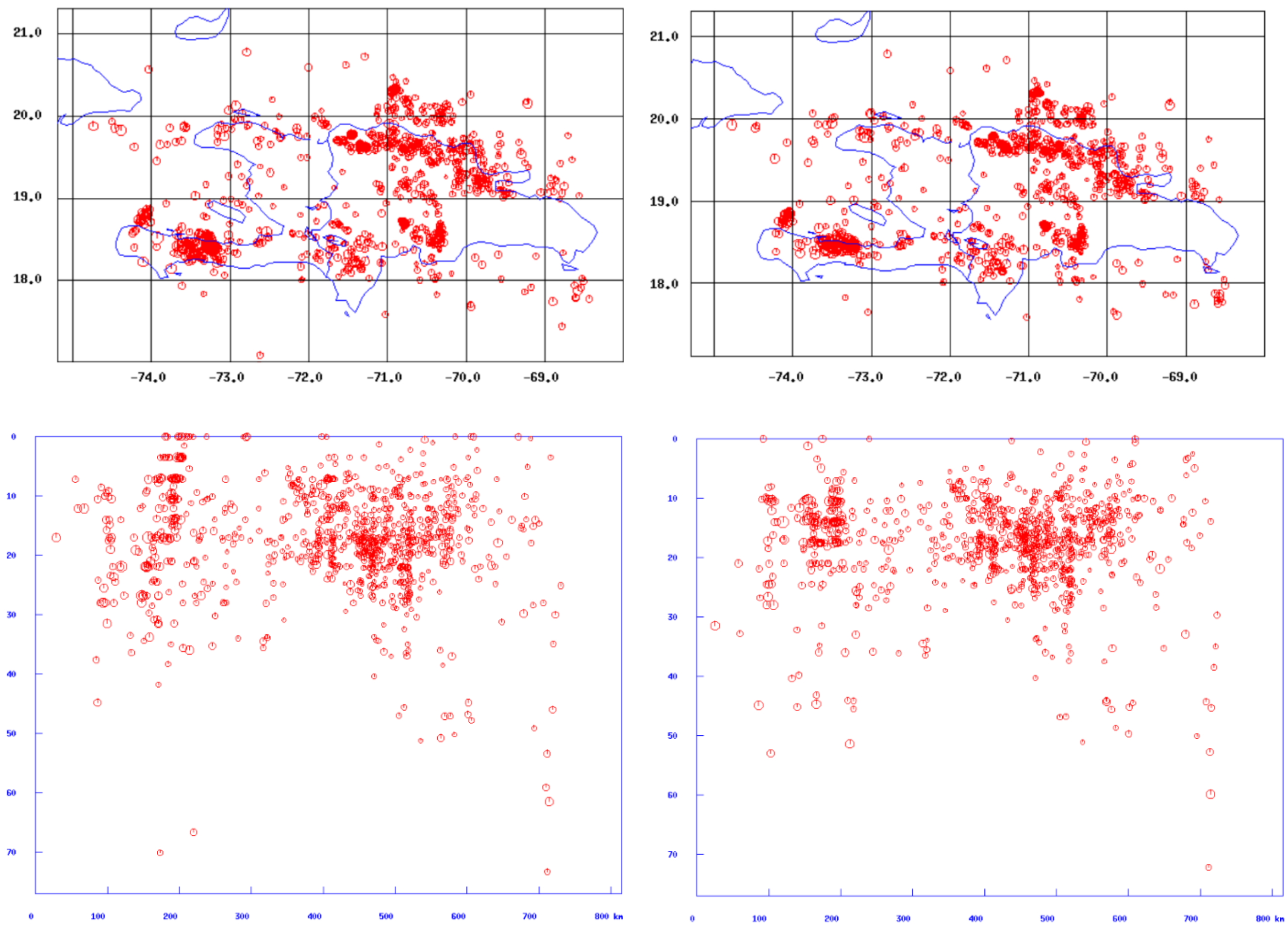
When comparing depths, all models show an increase in average hypocentral depth compared to the original depths (ORG) and the SDD models give the largest depths. This clearly indicate that the ORG model needs improvement.

It seems that using the new 200 km model with distances to 350 km only gives a little higher *rms* and similar average depth compared to using distances to 200 km. In general, it would be an advantage to use larger distances to make more stable results. In addition, some events cannot be located if we limit the distance to 200 km. We will compare the result using the NEW models with data to 200 and 350 km.

Table 5. Comparing the average differences between the results of using the NEW model with stations to 350 km and 200 km.

	Origin time (s)	RMS (s)	Latitude (deg)	Longitude (deg)	Depth (km)
Average difference	0.1	-0.1	-0.014	0.006	-0.4
Standard deviation	0.7	0.2	0.064	0.048	7.1

It is seen that the average difference in location is small. On average, the depths increase with 0.4 km using the 350 km model, but the standard deviation is 7 km. (Table 5). Figure 3 shows plots comparing the location with the 2 different distance limits. So, using the two distance ranges can give up to ca 5 km difference in hypocentral location.



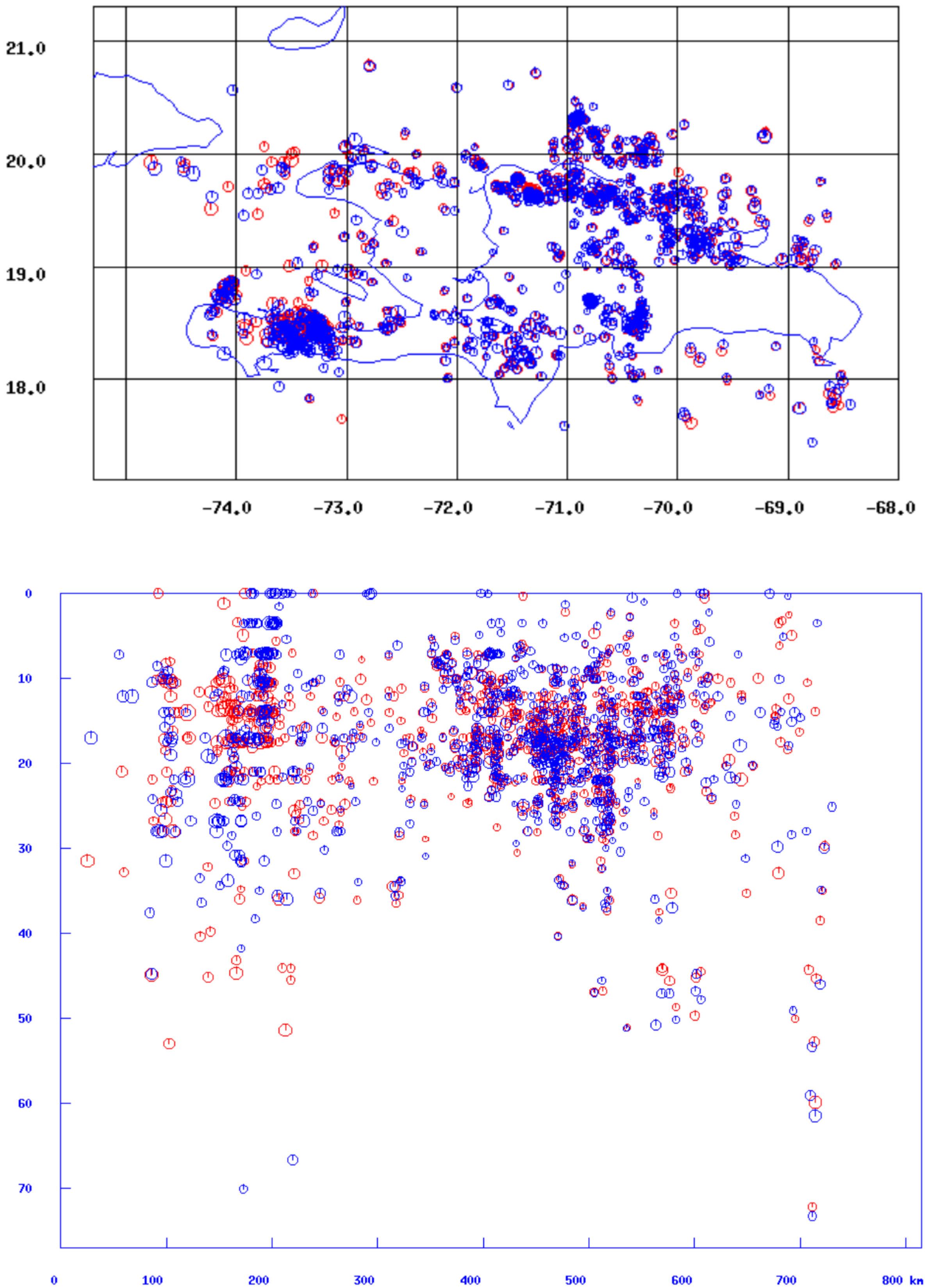


Figure 3. Comparative figures of hypocenters using the NEW model with data up to 200 km or 350 km respectively. *Top left*: Epicenters with stations to 200 km distance, *Top right*: epicenters with stations to

350 km distance, *Middle*: corresponding profiles from West to East, *Bottom*: Epicenters and profile for the 2 data sets together, blue is for 200 km and red for 350 km distance

Comparing the figures, it is seen that they look similar but with some significant differences. First, that the effect of using stations to 350 km instead of 200 km can have a significant effect on the location. The profiles are particularly different with fewer events with zero depth when using data to 350 km. This might indicate that for the less well located events, the added data to 350 km helps improve the depth of events giving zero depth for the 200 km model. The difference in depth between the 2 models clearly indicates that depth can be a very uncertain parameter. Using more stations further away will probably improve the epicenter but might make the depth less reliable. The difference in the hypocenters gives an idea of how large location errors might be for the less well-defined locations.

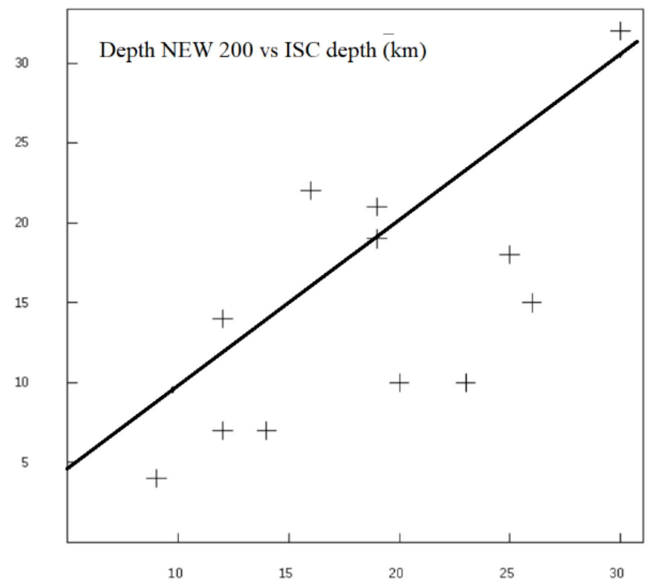
Depths

It is seen that the different models give different average depths. If the epicenter is surrounded by stations, then different models will mainly affect the depths. We have therefore compared some events located by ISC and NEIC to our location with different models and using different distances. Only ISC events with many phase readings are selected assuming that they have the most accurate depth. The events were selected from ISC with the requirement to be located by ISC using at least 150 phases. (Table 6)

Table 6. Compare depths calculated by the different models to ISC depths. The locations and origin times are from ISC. *Abbreviations*: OT: Origin time, lat: Latitude (degrees), lon: Longitude (degree), mag: Magnitude (mb), ISC: ISC depth, NEIC: NEIC depth, NEW: Depth with NEW model using data to 200 km, NEW 350: Depth with NEW using data to 350 km, SDD: Depth for SDD using 350 km. All depths are in km. The *'s indicates the 2 best located events.

	OT	lat	lon	Nst	mag	Distance to 3 near-rest stations (km)	ISC H	NEIC H	ORG H	NEW	NEW 350	SDD 350
1	2018 0923 05:45	19.636	-71.297	883	5.0*	24,47,62	19	20	6	19	19	24
2	2018 1111 18:02	19.729	-70.869	124	4.2	39,39.93	16	10F	1	22	22	29
3	2019 0502 12:40	17.989	-69.274	199	4.3	77,102,150	30	11	32	10	36	42
4	2019 0526 03:51	19.495	-70.437	135	4,0	31,61,104	23	10F	10	18	22	30
5	2020 0514 21:03	19.804	-71.113	271	4.3	5,63,64	19	10F	9	21	20	24
6	2020 0916 12:06	19.185	-69.852	264	4.4	18,85,95	25	29	9	18	19	22
7	2020 1019 09:00	19.091	-69.598	410	4.5	42,81,97	26	10F	0	15	15	22
8	2020 1130 11:12	18.213	-71.465	459	4.7*	15,16,42	12	10	2	7	8	18
9	2020 1213 06:07	19.557	-70.408	180	4.2	34,58,85	14	20	0	7	10	21
10	2021 0203 16:03	19.298	-68.881	157	4.4	44,95,107	9	10F	0	4	2	15
11	2021 0331 01:43	19.107	-68.881	143	3.9	32,88,111	20	8	0	10	11	14
12	2021 0906 04:38	19.031	-68.702	110	3.2	56,59,66	12	10F	0	14	10	17
	Average depth and sd						19 6	16 8	6 9	14 4	16 8	23 7

The original (ORG) depths are generally very shallow compared to ISC depths while all other models give larger depths. It is seen that ISC does not have any events with fixed depth as seen with the NEIC locations. This is probably due to more data available for ISC. It is seen that for the 2 best located events (indicated by * in the table), the depth given by ISC and NEIC are almost the same. So in general, ISC is expected to give more reliable depths. Comparing the average depths, one should then not compare to NEIC since all the fixed depths indicate unreliable depths and probably too shallow. The average depth for ISC is 19 while the NEW model shows 14. The SDD model gives too large depths compared to ISC while the NEW model shows too low depth compared to ISC. The NEW model at 350 km is a bit closer to ISC than the NEW model. However, the NEW model gives significantly lower *rms* than the SDD model (Table 4) so it seems that the NEW model to 350 km should be used. Figure 4 shows a comparison of ISC and test models depths.



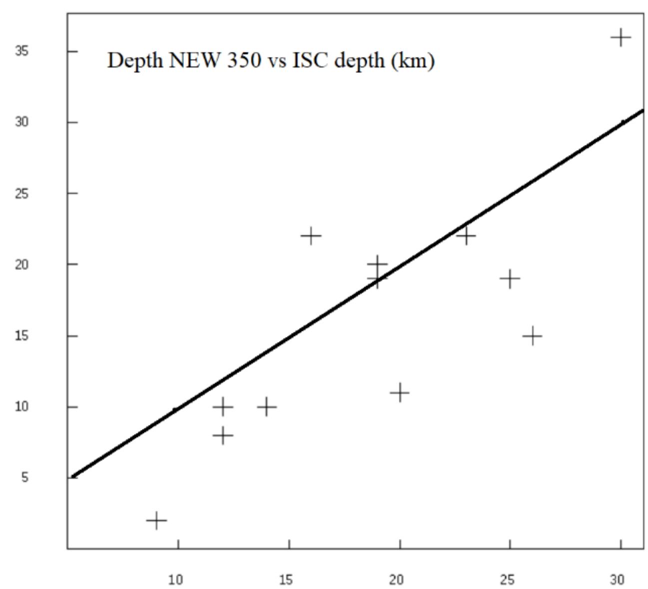


Figure 4. Comparing depths from ISC to depths using the NEW model with two different distances. The line shows the 1:1 relationship. Note that the y-scale of the axis is different in the 2 figures, so the scattering of the data appears different.

The figure shows that there is quite a bit of scatter in the comparison, but there is a clear linear relation between the two depths. vent number one is the best ISC located event of all. It has the most stations and in addition a pP depth of 20 km which is also the calculated ISC depth. The other events do not have pP depth and therefore are less reliable. The network depth should also be well located since it has 3 stations within 62 km distance. It is seen that the NEW model, using both 200 and 350 km limit gives the same depth as the ISC depth. Event # 8 is also well located by ISC with 459 stations and the event also has 5 stations within 48 km. The NEW model gives 4 km less than the ISC while SDD gives 6 km more. In Table 7, we have compared, for the 2 best located events, the difference in hypocenters between ISC and OSPL for all models.

Table 7. Comparing the locations of the 2 best located events to the location from ISC. The model names are defined in Table 4. Abbreviations: Ev: Event number, Dist: Max distance (km) to stations, Gap: Gap in azimuthal station coverage (degrees). Differences from ISC solution: Do: Origin time (s), Dx: Longitude (km), Dy: Latitude (km), Dz: Depth (km), The calculated location errors: erro: Origin time (s), erry: Latitude (km), errx: Longitude (km) and errz: Depth (km).

Ev	Model	Dist	Gap	Rms	Do	Dx	Dy	Dz	erro	erry	errx	errz
1	NEW	200	121	0.48	1.0	3.1	1.3	-0.3	1.1	3.2	2.8	6.0
	NEW	350	83	0.62	0.9	2.9	3.3	0.1	1.6	3.3	3.6	4.8
	SDD	350	85	0.72	-0.9	3.6	1.3	5.1	1.5	3.2	3.3	4.1
8	NEW	200	75	0.60	-0.7	2.5	1.3	-4.3	1.3	2.5	3.8	3.3
	NEW	350	75	0.60	-0.8	2.5	1.8	-4.2	1.5	2.7	3.6	3.4
	SDD	350	73	0.80	-2.4	4.1	3.5	5.6	2.1	3.9	5.8	4.1

The NEW model using distances up to 200 km and 350 km gives almost the same deviation from ISC. The SDD model gives larger estimated errors than the NEW models and in particular larger depth than ISC. Note that the calculated errors are similar in magnitude to the difference in location compared to ISC. For well-located events with near stations, one should expect the absolute errors to be less than 5 km in any direction and probably less than 3 km in horizontal direction. For the less well located events we can expect larger errors as indicated by Figure 3. In Figure 4, it seems that in general depths using NEW models are shallower than ISC depths however, that is assuming that all ISC depths are correct which might not be the case for the less well located ISC events. For the best located event from ISC (#1) the OSPL depth is the same as the ISC depth. For the second best located ISC event (#8) there is a difference of 4 to 5 km, however, since the ISC does not have a pP depth for this event, the ISC event might be in error, despite the many arrival times.

Model below 44 km

Only shallow events were used to determine the crustal models; however, the region also has deep events. A similar grid search was done using deep events for a couple of layers below 44 km but the results were not conclusive. Most models indicate a velocity of around 8 km/s below 44 km so we will keep that for now. In order to test if this is reasonable, some deep events were selected at ISC for comparison, see Table 8 and Figure 5. The events were then relocated with the local data using the NEW model with stations up to 350 km.

Table 8. Deep events located by ISC, with ORG model and NEW model. Abbreviations are: lat: latitude (degree), lon: longitude (degree), nstat: number of stations used by ISC (999 means more then 999), ISC: depth (km) given by ISC, ORG: depths (km) calculated using the ORG model and NEW: depths (km) calculated using the NEW model.

year	month day	hr min	sec	lat	lon	nstat	ISC	ORG	NEW
2018	0603	0913	20. 0	18.873	-69.640	850	84	84	83
2018	0621	0013	51.7	18.913	-69.855	229	88	86	83
2018	0804	1142	15.3	18.420	-68.704	168	160	171	162
2018	1206	0551	49.3	18.490	-68.891	131	128	130	126
2018	1222	1412	16.7	18.566	-69.074	229	124	131	126
2019	0204	1433	48.1	17.996	-68.597	999	72	63	60
2019	0630	0637	53.4	18.446	-68.899	226	118	103	115
2019	0728	1602	10.5	18.396	-68.990	336	140	151	129
2019	1125	0935	38.1	18.521	-69.180	68	148	148	134
2020	0105	0829	00.2	18.346	-69.019	169	124	131	118
2020	1007	1414	26.1	19.069	-70.440	113	96	93	89
2021	0516	1214	50.1	18.834	-70.345	313	90	99	91
2021	0614	1015	42.7	18.037	-68.523	999	88	74	75
2021	0624	0456	46.7	18.312	-68.545	169	152	161	151
2021	0928	0015	35.8	18.754	-69.362	207	108	108	106
Average							115	115	110

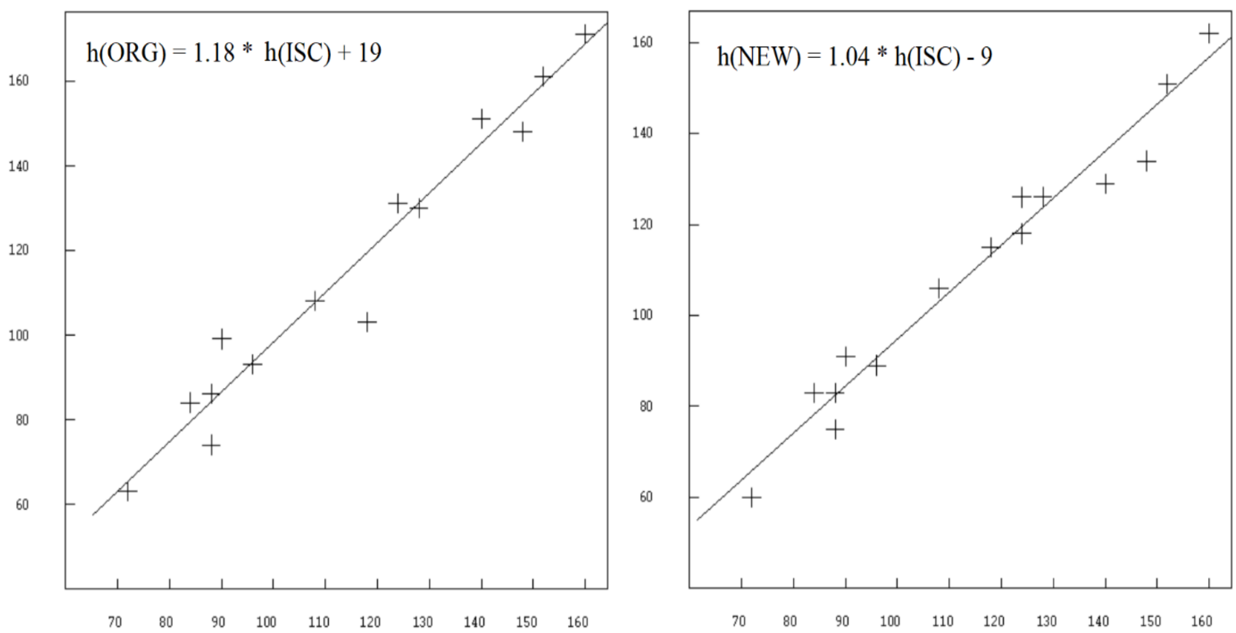


Figure 5. Comparing hypocentral depths (km) for some events located by ISC and located by the ORG model (left) and NEW model (right). The black line is the least squares line.

It is seen that both the ORG model and the NEW model give depths very close to the ISC depths so one layer below 44 km at 8.0 km/s seems reasonable. From Figure 5 it is seen that the NEW model gives depths a bit closer to the ISC depths than the ORG model, probably due to the more correct upper layer velocities. In any case the test shows that the OSPL network can calculate correct values for deep events in the area.

Discussion

The NEW model clearly seems the best overall average model. In order to ensure that all events can be located, it should be used with a distance to 350 km. The test also indicates that using distances to 350 km give similar hypocenters than using 200 km although, there are also significant differences.

However, all the tests illustrate how difficult it is to get an appropriate average model of the area considering its 3D nature. Ideally different models should be used for different areas but that would be impractical in practice and making it difficult to get a spatially continuous picture of the area. Using 3D location would be the ideal situation, but programs for 3D location are not readily available. It is also clear that the hypocentral depth for shallow events is the most difficult parameter to estimate reliably, particularly if there are no near stations. For deep events it is much easier to get correct depths using local stations due to the angle of incidence is far from horizontal, so the depth is more sensitive to the arrival times. For the OSPL network it is recommended to use the NEW model to 350 km distance, but when possible test for depth with the model to 200 km. There is no doubt that the new model will improve the hypocenter accuracy, particularly with respect to depth. However, this is strictly not a correct model, just a model that in an average sense gives the best fit to the test data. Using a different test data set might have given a different model.

References

Havskov J, Voss P and Ottemöller L. (2020). Seismological observatory software: Thirty years of SEISAN. Seismological Research Letters, 91, 1846-1852.

International Seismological Centre (2023), On-line Bulletin, https://doi.org/10.31905/D808B830

Núñez D, Córdoba D, and E. Kissling (2019). Seismic structure of the crust in the western Dominican Republic (2019). Tectonophysics. https://doi.org/10.1016/j.tecto.2019.228224

Rodríguez J, Havskov J, Bøttger Sørensen, M and Santos, L F. (2018). Seismotectonics of south-west Dominican Republic using recent data. Journal of Seismology, 4, 883-896. https://doi.org/10.1007/s10950-018-9738-9