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Teleseismic depth determination, techniques and uncertainties : an Himalayan case study

Marine Laporte[1,2,3], Jean Letort[2], Laurent Bollinger[1], Lok Bijaya Adhikari[4], Yoann Cano[1]

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ORAL PRESENTATION

Teleseismic depth determination, techniques and uncertainties : an Himalayan case study

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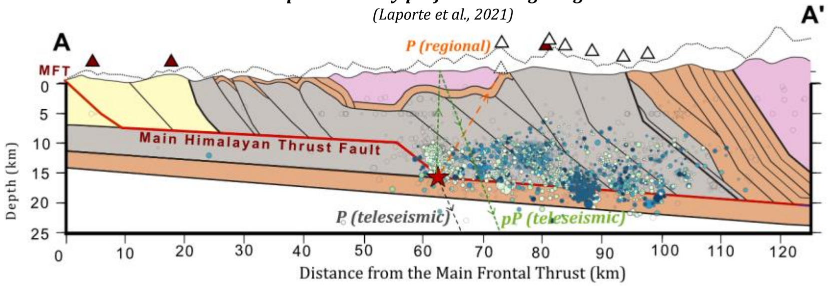
Introduction

At regional distance

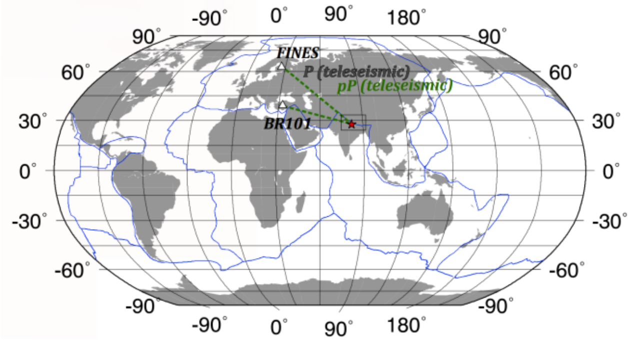
All range of magnitudes
Relies on S-P delay
Requires regional/local networks

Far Western Nepal seismicity projected on a geological cross-section
(Laporte et al., 2021)



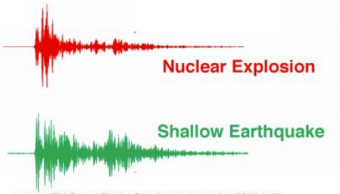
At teleseismic distance

Moderate-magnitude events
(M>3.5)
Relies on pP-P or sP-P delays
Using Global Seismological networks
(FDSN / IMS-CTBTO)



Why improving depth determination ?

- Seismotectonic studies
  (Slab geometry, lateral variation of main tectonic structures)
- Discrimination between earthquakes and explosions



source : The Source Physics Experiment science plan (2014) LLNL

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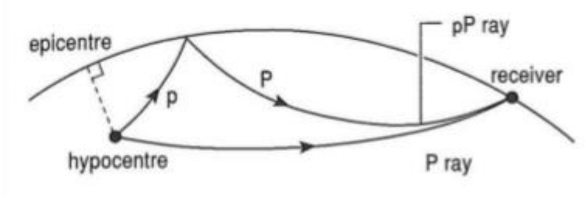
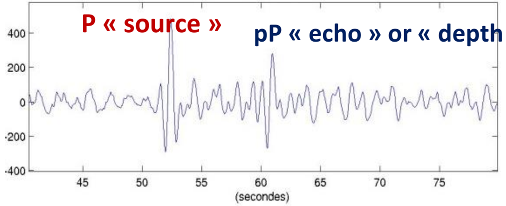
1- Techniques : Description of a teleseismic signal

Teleseismic wave = Direct wave (P) + P and S direct waves reflected on the Earth's surface (pP/sP)





Main characteristics of *« depth phases »* pP/sP:

- Recorded at stations between 30° (3000 km) to 90° (10000 km) away from the source
- Emitted rays are nearly verticals (< 30°)

Delays pP-P and sP-P are function of the hypocentral depth and the crustal velocity model above the source

Objective : Improving the detection of reflected waves « echoes » in the teleseismic signal

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1- Techniques : Cepstrum analysis

- **Cepstrum :** « the power spectrum of the logarithm of the power spectrum »

Application : Detection of echoes in a seismic signal — *Bogert et al., 1963*

0. Signal *(seconds)*

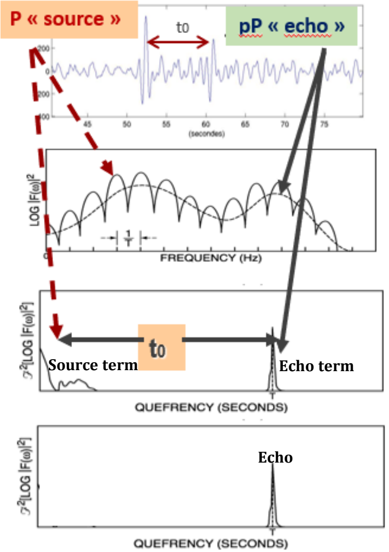
Fourier Transform

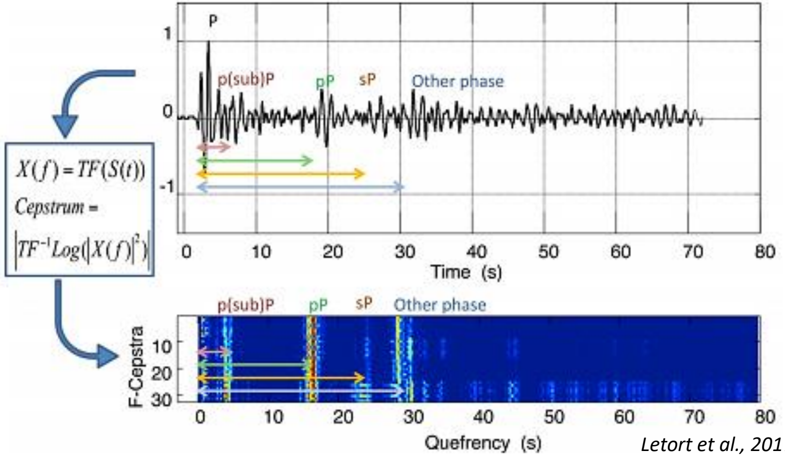
1. Spectrum *(frequency)*

Fourier Transform

2. Spectrum(Log(Spectrum)) = Cepstrum *(quefrency)*

3. Substraction of the source term *(quefrency)*





Letort et al., 2017

Letort et al., 2014 : **Automatic** depth determination after station selection

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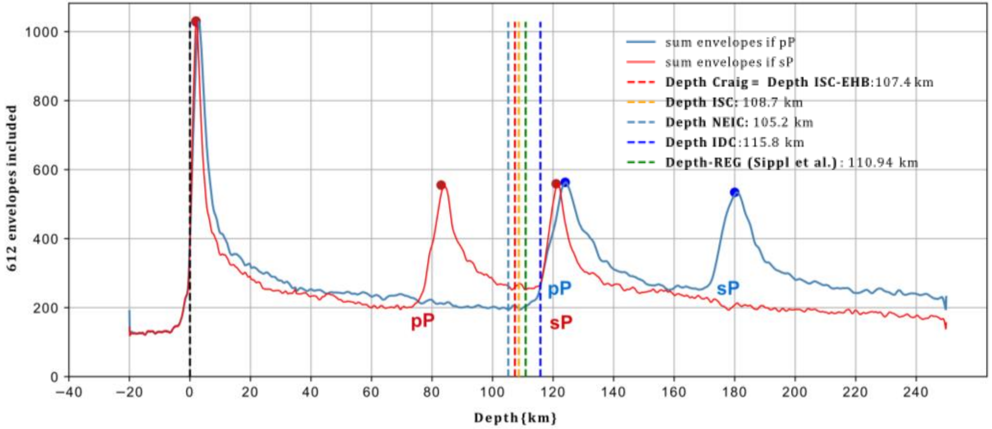
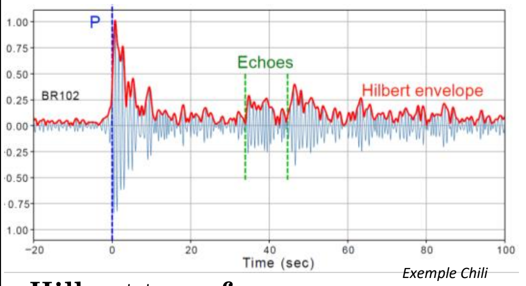
1- Techniques : Stack of Hilbert envelopes

1 - **Cross-correlation + stack** of small-aperture arrays
2– **Align** all waveforms on the direct phase using an improved kurtosis (Baillard et al., 2014) (filter : 0.8-2.5 Hz)
3 - Lecture of P-pP et P-sP table as a function of array distance and source depth- ak135 velocity model
4 – **Depth migration** of stacked signals : case pP / case sP (time → depth)
5 – **Sum of Hilbert envelopes** at each station for each case (pP/sP)

A **manual** method for picking depth phases (interactive figure)



Depth corresponds to the coherent peaks pP + sP



Hilbert transform

Linear operator given by the signal convolution with the function $\frac{1}{\pi t}$

Other depth determination techniques :

. Waveform inversions (i.e. Abe, 1974; Langston, 1976)
. Global array stacking and source deconvolution (Craig et al., 2018)
. Stacking distance-variable window on binary functions representing potential arrival (Murphy and Barker, 2006)
...

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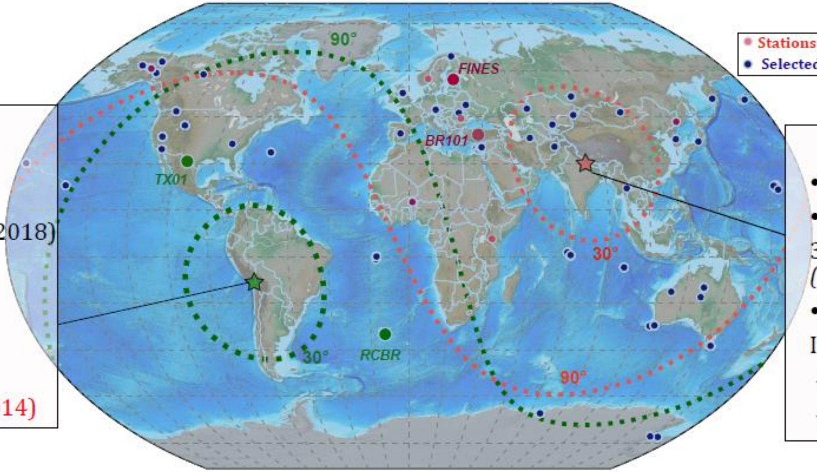
2- Data : Selecting world-wide datasets

1 - Chili

- Hypocentral depths : **[0-300] km**
- **Regional constraints :**
  10,000 events + uncertainties (Sippl et al., 2018)
- **Teleseismic depths catalogs (4 sets):**

ISC-EHB depths
Source deconvolution (Craig et al., 2018)
+ Sum of Hilbert envelopes
+ Cepstrum analysis (based on Letort et al., 2014)



2- Nepal

- Hypocentral depths : **[0-25] km**
- **Regional constraints :**

38 events (MLv> 3.5) + uncertainties *(Laporte et al., 2021)*

- **A distance télésismique:**

ISC -EHB depths
+ Sum of Hilbert envelopes
+ Cepstrum analysis

✓ *1st objective :*
Validation of teleseismic depth determination techniques
Comparison between global networks FDSN/IMS
1 – Chili : Large dataset of moderate magnitude events (M>4) with a wide-range of depths

✓ *2nd objective :*
Finding limits of teleseismic depth determination techniques for shallow events

2a – Far Western Nepal : Dataset of moderate magnitudes (ML>3.5) shallow events
2b – Central Nepal : Multi-technique study of the 2021 Lamjung seismic crisis

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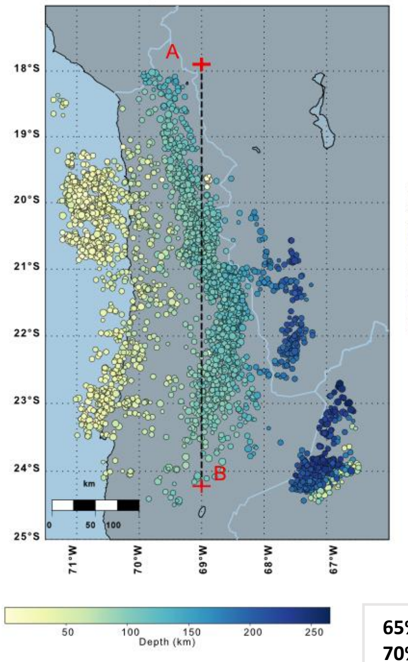
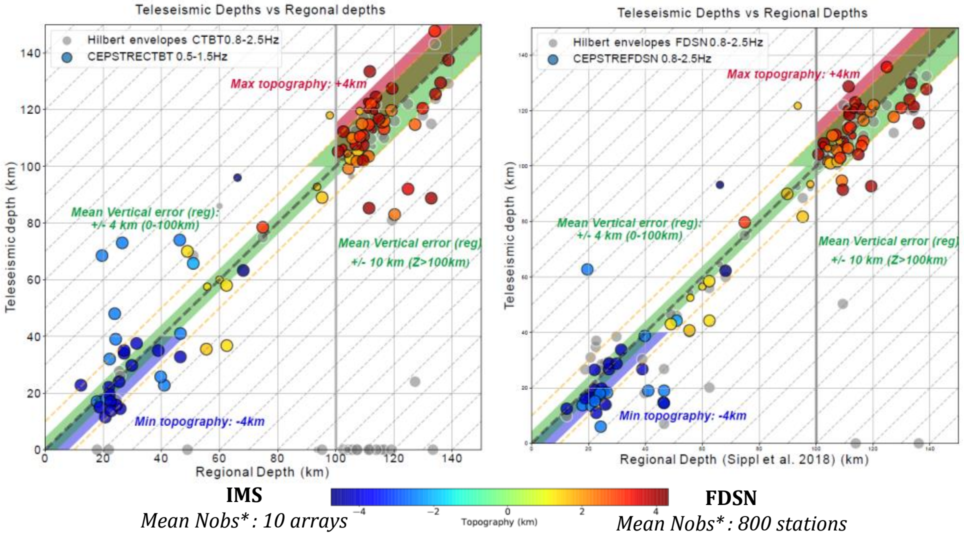
Case study n°1: Northern Chile Forearc

Seismicity from Sippl et al., 2018



Comparison of teleseismic depths (Cepstrum, Hilbert) with regional depths



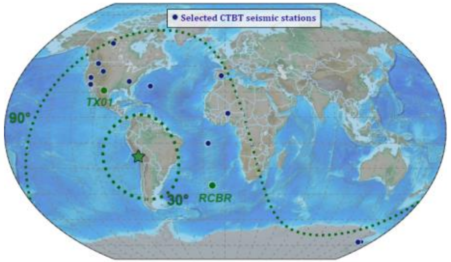
IMS
Mean Nobs : 10 arrays*
Mean processing time : 15 sec

FDSN
Mean Nobs : 800 stations*
Mean processing time : 1000 sec

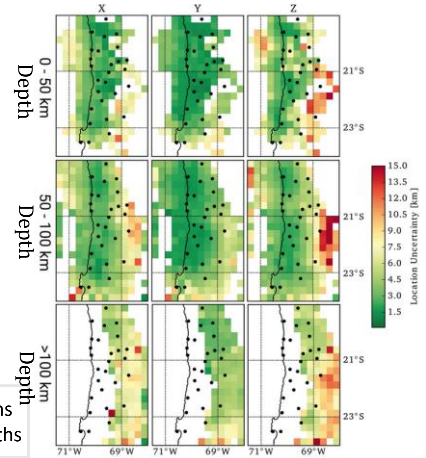
65% of Cepstrum depths within +/- 10 km of local depths
70% of Hilbert envelopes within +/- 10 km of local depths

71% of Cepstrum depths within +/- 10 km of local depths
78% of Hilbert envelopes within +/- 10 km of local depths

**Nobs : Number of observations*



***Map of** (Sippl et al., 2018)*



***Regional location uncertainties** (Sippl et al., 2018)*

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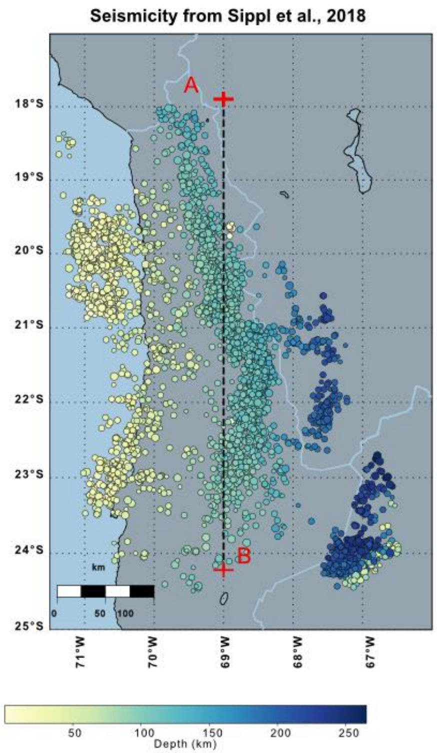
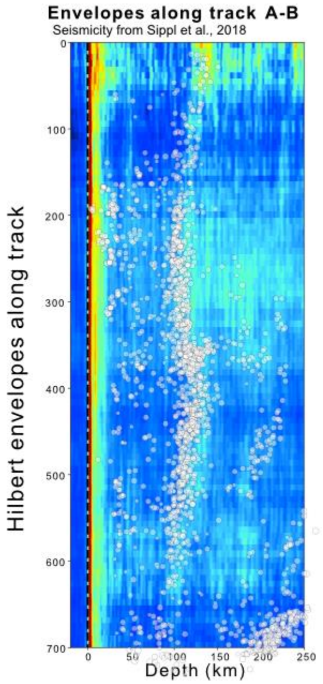
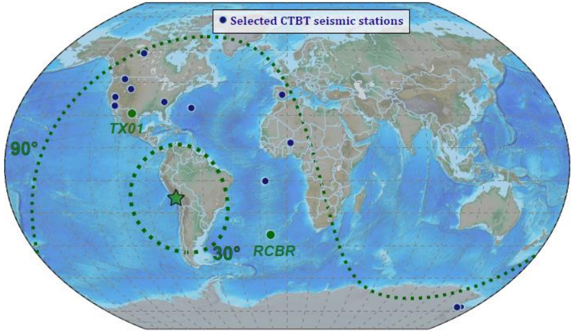
Case study n°1: Northern Chile Forearc







Using Hilbert envelopes for seismotectonic studies

(Letort et al., 2018 – Guerrero, Mexico)

- Seismic data from **only two IMS stations** *(TX01/RCBR)*
- Sum of Hilbert envelopes of events projected on track A-B
  - Cross correlation on mini-arrays *(cc>0.75)*
  - Filtering *0.8 – 2.5 Hz*
  - SNR > *3*

Objectives :

. To recover the chilean slab geometry using Hilbert envelopes of ~1000 events

. To provide an image of the lateral variations of the slab

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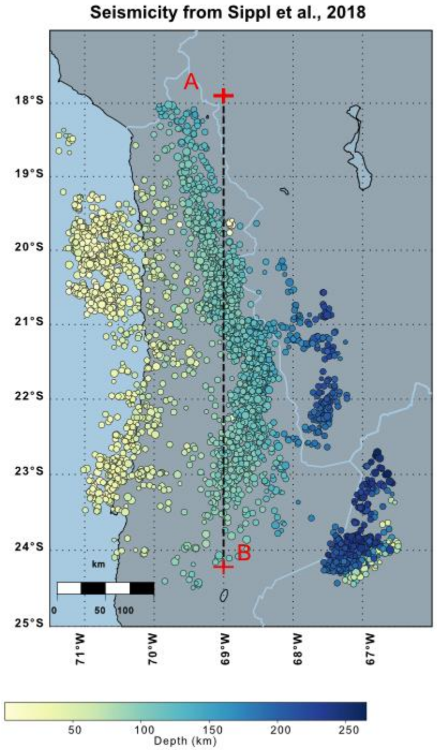
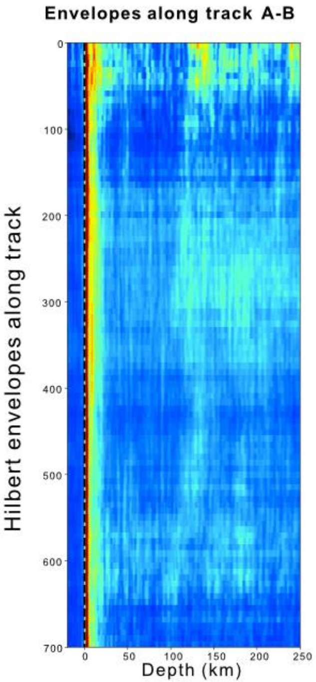
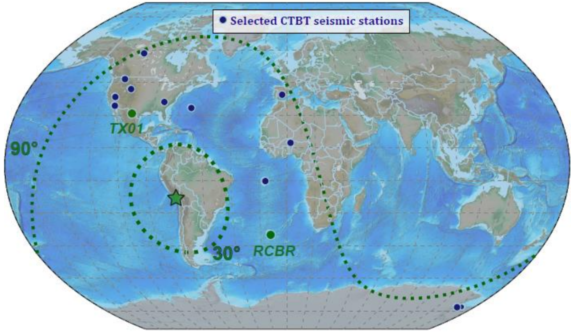




The energetical content of Hilbert envelopes reproduces the lateral variations of seismicity at depth



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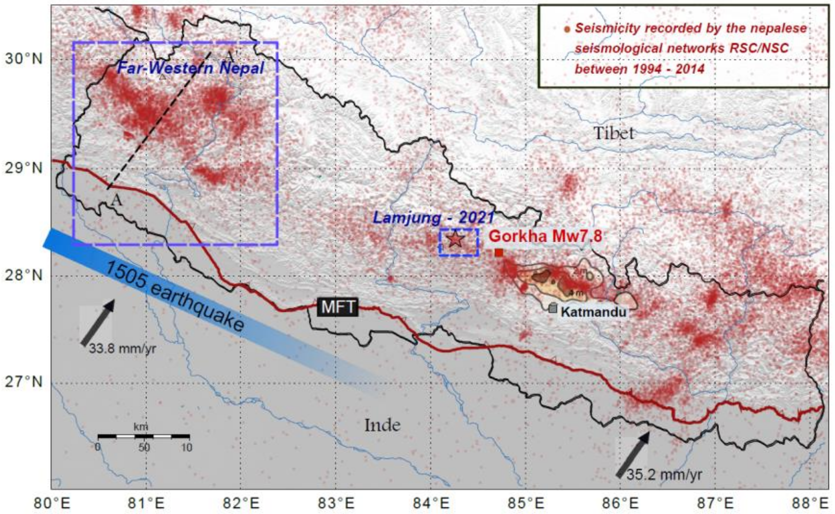
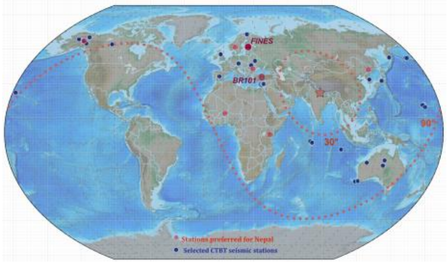
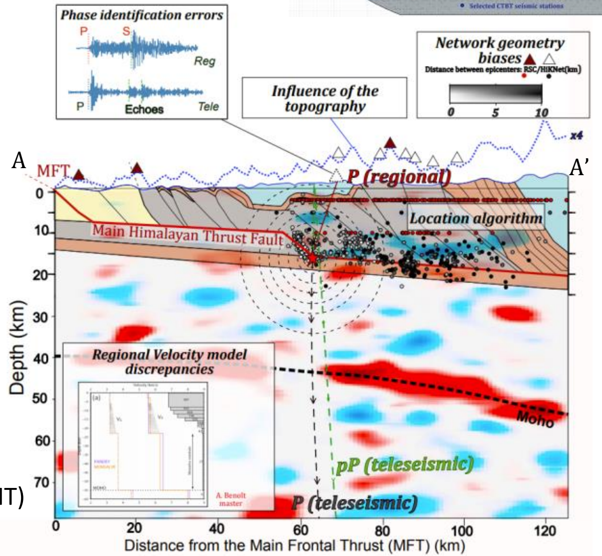
Case study n°2 : Nepal







Why an Himalayan case study ?

- High seismicity rates
- Nepalese seismicity occurs mainly between 10-25 km depth
- Studying the relation between shallow earthquakes and the Main Himalayan Thrust Fault (MHT)

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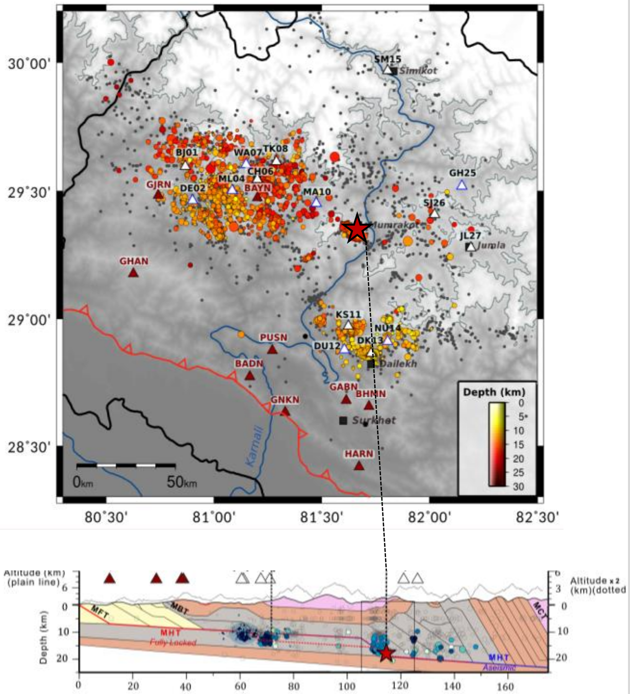
Far Western Nepal seismicity recorded by HiKNet temporary experiment
(Laporte et al., 2021)

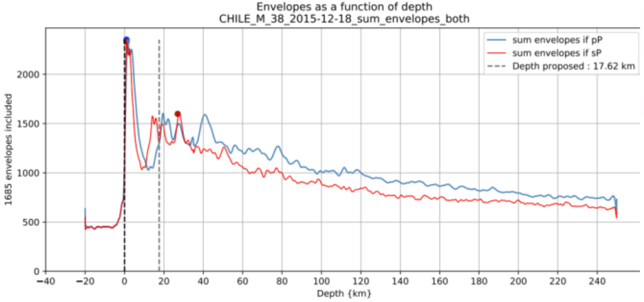


Case study n°2.a : Far-Western Nepal

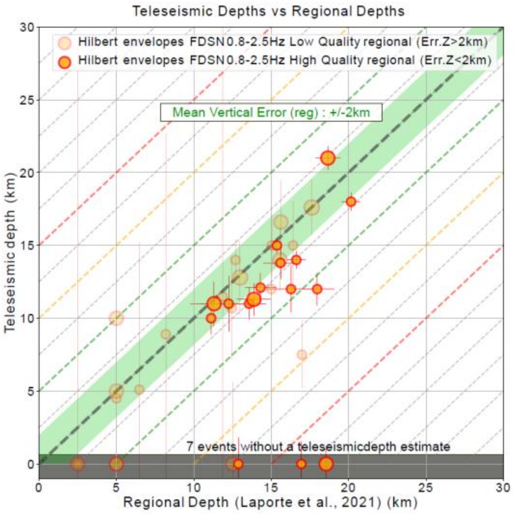
Comparison with depths from the HiKNet temporary seismological experiment (2014-2016)

38 events recorded at both regional and teleseismic distances with strong regional constraints

- 17 events considered as High Quality locations
  (nP>6, nS>3, rms<0.4, ERZ<2, ERH<2)



Exemple - MLv 5,2 – 2015.12.18 earthquake
Event located at the base of the mid-crustal ramp



*Comparison between **Teleseismic** (Hilbert) And **Regional** (Hypo71) depths*

5 events /17 within 2 km of regional depth
12 events/17 within 5 km of regional depth
3 events /17 without adequate teleseiismic depth

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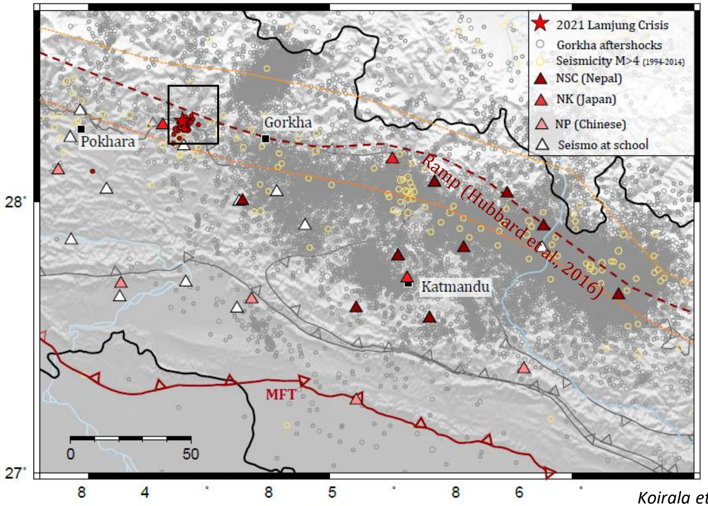
Case study n°2.b :

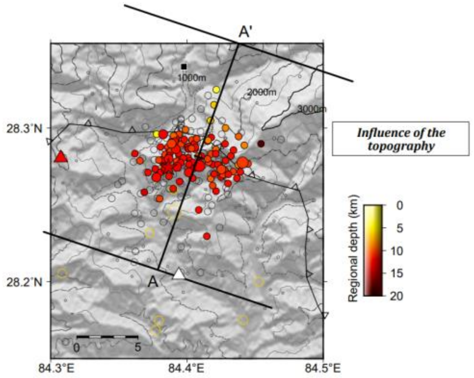
Regional and Teleseismic joint analysis of the Lamjung seismic crisis (Central Nepal)

Koirala B., Bollinger L., Guilhem-Trilla A., Laporte M., Daria, Wendling-Vasquez N., Letort J.,

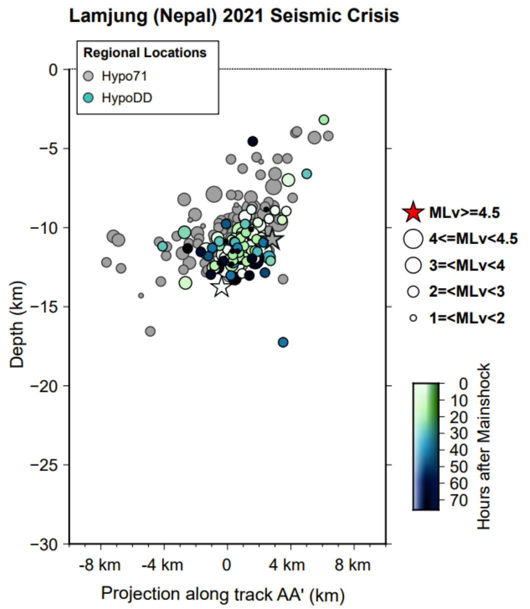
Lamjung seismic crisis :

- **Mainshock :** MLv 5.5/Mw 4.69 – 2021.05.18-23:57:57 (UTC)
- Followed by 110 aftershocks within 5 days
- No signs of seismic swarm-like migration





Koirala et al., in prep



Crucial parameter for seismotectonic interpretation

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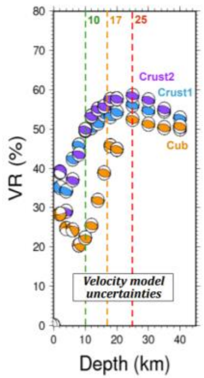
Four depths solutions for the mainshock :

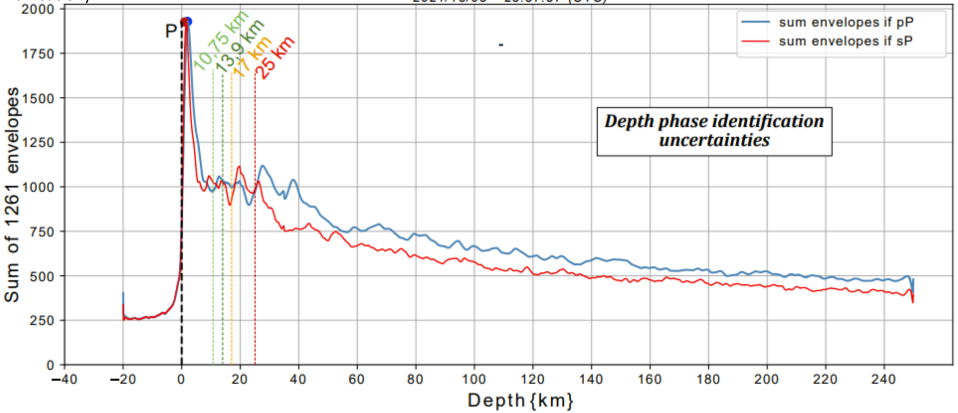
- **10,75 km :** Hypo71(absolute, regional)
- **13,8 km** : HypoDD (relative, regional)
- **17 km** : Cepstrum analysis – MT inversion
- **25 km :** MT inversion

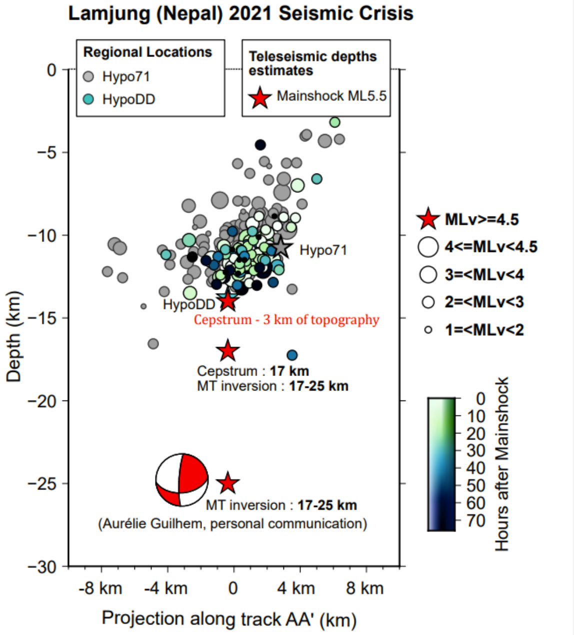
→ ***Uncertainties :*** *Regional velocity model (+/- 5km) (Adhikari., 2021), network geometry (regional only), topography (-3km), complex slab geometry, teleseismic wave interferences ?*

Regional Moment Tensor inversion
(Aurelie Guilhem, personal communication)



Sum of envelopes as a function of depth
Lamjung Mainshock Mw 4.69
2021/18/05 - 23:57:57 (UTC)





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Conclusion

Objectives :

- **Development of a new manual method** for determining hypocentral depth from global teleseismic network using the **Hilbert envelopes of teleseismic waveforms**
- **Using regional seismic catalogs with well-constrained depths** to **point out errors** in the depth determinations at teleseismic distance
- **Highlighting lateral variations of geometry of large tectonic structures** (slab, megathrusts…) using projections of Hilbert envelopes of large seismic datasets seen at one or two teleseismic stations

Results :

- Comparisons of teleseismic depths with depths constrained by regional seismological networks (Chile, Nepal)

→ In Chile **: 71 %** of teleseismic depths within +/-10 km of regional depths (out of 100 events)

- Projections of stacked Hilbert envelopes of 1000 earthquakes recorded at TX01 and RCBR highlights lateral variations of the northern chilean slab
- Determination of the limits of each depth determination technique : for shallow events in complex tectonic environments conjoint studies of regional and teleseismic depth determination techniques do not always succeed to find a common depth result

Perspectives :

- Quantification of uncertainties and their propagation into the Cepstrum analysis and Hilbert technique
- Finding source of depth errors for the Lamjung crisis
- Application of the projection of Hilbert Envelopes for Himalayan regions

References

References for the Cepstrum analysis :

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