



UNIVERSITAT DE
BARCELONA

Shear Waves Characterization of the Sub-surface: Imaging Active Fault and Critical Zone along the Eastern Betic Shear Zone, SE Iberian Peninsula

Handoyo



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Ph.D Student : ***Handoyo***

Supervisor : ***Prof. Ramon Carbonell***

Co-Supervisor : ***Dr. Juan Alcalde***

Tutor : ***Prof. Alejandro Marcuello***

Geociencias Barcelona - GEO3BCN
Consejo Superior de Investigaciones Científicas - CSIC



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*To obtain the degree of doctor from the University of Barcelona
Thesis conducted within the framework of The Doctoral programme
of Universitat de Barcelona*

Ph.D Student: ***Handoyo*** _____

Supervisor: ***Prof. Ramon Carbonell*** _____

Co-supervisor: ***Dr. Juan Alcalde*** _____

Tutor: ***Prof. Alejandro Marcuello*** _____

Barcelona, November 2022

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ABSTRACT

The Earth System is formed by four components that sustain life: the atmosphere, the biosphere, the hydrosphere and the geosphere. The complex region in which these elements interact is known as the 'Critical Zone'. The critical zone (CZ) is crucial for our society, as it is host of a diverse range of hydrological, geochemical, and biological processes that operate on numerous scales and shape landscapes, support ecosystems, and control resource availability. The CZ and by extension the shallow subsurface is also the host to human activity and infrastructure, and it is therefore vulnerable to natural hazards, such as extreme weather events, volcanic activity or earthquakes. Thus, it is key to investigate and monitor the shallow subsurface, to understand its geometry, extent and physical properties in order to produce comprehensive hazard assessments that could take place in connection to this important layer.

The southeastern part of the Iberian Peninsula is characterized by moderate but intense earthquake activity that has caused significant damage since historical times. The seismicity in that area is distributed within a relatively broad deformation band parallel to the coast that includes a well-developed strike-slip fracture system. This deformation band is known as the Eastern Betic Shear Zone (EBSZ) and, runs along the southern border of the Guadalentín Depression, it is a densely populated area with extensive agricultural activity. Therefore, the activity of the faults in the EBSZ represents a seismic hazard with a very significant social and economic impact potential. This memoir focuses in the characterization of the shallow sub-surface structure including the CZ and, characteristics of the Carrascoy and Alhama de Murcia fault systems, SE Iberian Peninsula. To achieve this characterization, different shear wave seismic velocity-depth models based on Multichannel Analysis of Surface Waves (MASW) were constructed. These models were complemented with investigations involving P-wave tomography and/or Electrical Resistivity Tomography (ERT) methods, as well as surface geological observations (e.g. mapping and paleoseismological trench studies) to constrain physical properties models of the subsurface. S-wave velocities were estimated from the surface waves recorded within the controlled-source shot

records of conventional normal incidence seismic reflection data. P-wave velocity models were determined from first arrival travel-time tomography. The resulting velocity-depth models revealed: i) the location, geometry and extent of shallow fault zones, and their associated damaged unconsolidated zones, new blind faults were also identified; ii) the thickness of the critical zone and its relation with fault zones in the target areas; and, iii) provide valuable information about the fault network for seismic hazard assessments.

The seismic signature of the fault zones, including these of the multiple blind faults and fractured zones identified in the different profiles, was well demonstrated using 2D velocity depth models (S- and P- waves). Seismic signatures of fault zones and blind faults are indicated in the models by low-velocity anomalies. Vs velocities in the range of 500-1000 m/s and Vp within the range of 1300-1700 m/s. These low values indicate a reduced bulk- and shear-modulus along and around the fault plane. The velocity model images across the Carrascoy and La Torrecilla reveal higher number of faults than what is imaged in the La Salud South and La Salud North profiles. This might be indicative of differences in the maturity degree of the fracture zones involved. Being the former more mature than the latter.

The models obtained have resolved the geometry and characteristics of the CZ in the neighborhood of faults/fracture zones. It is characterized consistently by relatively low seismic velocities $V_s < 600$ m/s and $V_p < 1300$ m/s, which is consistent with the expected low resistivity layer of Quaternary alluvial unconsolidated sediments in the La Torrecilla, La Salud North, and La Salud South profiles, as well as the Unidad Roja (Red Unit) and the Pleistocene-Quaternary alluvial in the Carrascoy profile. The thickness of the CZ in La Salud North profile lies within the range from 35-45 m and in La Salud South profile within 40-47.5 m. Furthermore, the thickest CZ layer constrained in the La Torrecilla profile features a thickness of *ca.* 40-50 m. The thinnest CZ is located in the Carrascoy profile with a thickness of *ca.* 30-40 m.

In addition, the results also reveal a relation between fracture/fault zones and the thickness of the CZ. The presence of faults can contribute to the observed topography of the CZ in two ways:

changes in bedrock elevation as a consequence of fault geometry changes and/or an increase in the number of regolith layer fragments, with the CZ layer near the fault zone becoming relatively thicker than in places far away from the fault zone.

The shear wave characterization of the sub-surface presented in this memoir provides a methodological and workflow protocol to study the shallow subsurface in areas with active deformation, providing geometry and depth constraints to the structures interpreted in the geological models based on paleoseismological trenches, and, therefore, these can be used for improving the seismic hazard assessment and provide a detailed characterization of the CZ of this and other tectonically active regions in the world.

Keywords: Alhama de Murcia Fault, critical zone (CZ), MASW, P- wave tomography, surface waves

RESUMEN

El Sistema Tierra está formado por cuatro componentes que sustentan la vida: la atmósfera, la biosfera, la hidrosfera y la geosfera. La compleja región en la que interactúan estos elementos es conocida como la ‘Zona Crítica’. La zona crítica (CZ) es crucial para nuestra sociedad, ya que alberga una amplia gama de procesos hidrológicos, geoquímicos y biológicos que operan a numerosas escalas y dan forma a los paisajes, sustentan los ecosistemas y controlan la disponibilidad de recursos. La CZ y por extensión el subsuelo poco profundo albergan la actividad y las infraestructuras socialmente útiles, por lo que son vulnerables a los riesgos naturales, como los fenómenos meteorológicos extremos, la actividad volcánica o los terremotos. Por ello, es fundamental investigar y monitorizar la CZ, para comprender su geometría, extensión y propiedades físicas con el fin de elaborar evaluaciones completas de los peligros que podrían producirse en relación con esta zona tan importante.

El sureste de la Península Ibérica se caracteriza por una moderada pero intensa actividad sísmica que ha causado importantes daños desde tiempos históricos. La sismicidad en esa zona se distribuye a lo largo de una banda de deformación relativamente amplia, paralela a la costa, formada por un sistema de fallas con deslizamientos bien desarrollados, conocida como Zona de Cizalla Bética Oriental (ZCBO). La ZCBO, que discurre a lo largo del límite sur de la Depresión del Guadalentín, es una zona densamente poblada y con una gran actividad agrícola. Por lo tanto, la actividad de las fallas en la ZCBO representan un peligro sísmico con un impacto social y económico potencialmente muy significativo.

Esta memoria se centra en la caracterización de la estructura y características-naturaleza del subsuelo somero de los sistemas de fallas/fracturas de Carrascoy y Alhama de Murcia, en el SE de la Península Ibérica. Para lograr esta caracterización, se construyeron diferentes modelos de velocidad-profundidad de ondas de cizalla basados en el Análisis Multicanal de Ondas Superficiales (MASW siglas en Inglés). Se construyeron también modelos de ondas P, y de resistividad mediante métodos de tomografía de ondas P y/o Tomografía de Resistividad Eléctrica

(ERT). También se incorporaron estudios de geología de superficie (por ejemplo, cartografía geológica y estudio de paleosismicidad, trincheras) para proporcionar modelos de propiedades físicas del subsuelo. Las velocidades de las ondas S se estimaron a partir de las ondas superficiales registradas en datos de sísmica de reflexión de incidencia vertical convencional (fuente controlada). La velocidad de las ondas P se determinó a partir de la tomografía de tiempos de viaje de las primeras llegadas de los mismos registros. Los modelos resultantes contribuyeron a determinar los siguientes puntos: i) la identificación de zonas de fallas poco profundas, incluidas una serie de fallas ciegas desconocidas hasta el momento; ii) el grosor de la zona crítica y su relación con las zonas de fallas en las áreas de estudio; y iii) proporcionar información valiosa sobre la red de fallas para las evaluaciones de riesgo sísmico.

La firma sísmica de las zonas de falla, incluidas las de las múltiples fallas ciegas y las zonas fracturadas identificadas en los diferentes perfiles, quedó bien reflejada en los modelos de velocidad en función de la profundidad 2D (ondas -S y -P). Las zonas de fractura incluidas las fallas ciegas se caracterizan por reflejar anomalías de velocidad relativamente baja en el orden de V_s 500-1000 m/s y V_p 1300-1700 m/s, esto refleja una reducción de los módulos bulk y de cizalla en el entorno y a lo largo del plano de falla. Los perfiles de Carrascoy y La Torrecilla presentan mayores concentraciones de zonas de fractura (falla) que los perfiles de La Salud Sur y La Salud Norte. Esta disminución posiblemente indica zona de fallas menos maduras.

La zona crítica (CZ) se caracteriza, en general, por presentar anomalías de bajas velocidades sísmicas $V_s < 600$ m/s y $V_p < 1300$ m/s, lo cual se congelaciona con la capa de baja resistividad esperada en los sedimentos aluviales poco consolidados del Cuaternario en los perfiles de La Torrecilla, La Salud Norte y La Salud Sur, así como la Unidad Roja y el aluvial Pleistoceno-Cuaternario en el perfil de Carrascoy. El espesor de la CZ en el perfil de La Salud Norte oscila entre los 35-45 m y en el perfil de La Salud Sur entre los 40-47,5 m. Además, la capa de CZ más gruesa aparece en el perfil de La Torrecilla con un espesor de unos 40-50 m y la CZ más fina se encuentra en el perfil de Carrascoy con un espesor de unos 30-40 m.

Los modelos también revelan la relación de las zonas de fallas, zonas mas fracturadas con el espesor de la CZ. La presencia de fallas puede contribuir a la topografía observada de la CZ de dos maneras: cambios en la elevación del basamento rocoso como consecuencia de los cambios en la geometría de las fallas y/o un aumento en el número de fragmentos de la capa de regolito, siendo la capa de la CZ cerca de la zona de falla relativamente más gruesa que en lugares alejados de la zona de falla.

La caracterización de las ondas de cizalla del subsuelo que se presenta en este trabajo proporciona un protocolo metodológico y de retroalimentación para estudiar la CZ y por extensión el subsuelo mas somero en el entorno de redes de fracturación, y fallas, proporcionando información sobre su geometría y extensión en profundidad reduciendo la incertidumbre de los modelos geológicos previos basados en trincheras paleosismológicas, y, por tanto, éstos pueden utilizarse para mejorar la evaluación de la peligrosidad sísmica y el estudio de las zonas críticas (CZ) de ésta y otras regiones tectónicamente activas.

Palabras clave: falla de Alhama de Murcia, falla de Carrascoy, zona crítica (CZ), MASW, tomografía de ondas -P, ondas superficiales.

RESUM

El sistema terra està format per quatre components que sustenten la vida: l'atmosfera, la biosfera, la hidrosfera i la geosfera. La complexa regió on interactuen aquests elements es coneguda com la 'Zona Crítica'. La zona crítica (CZ) és crucial per a la nostra societat, ja que acull una àmplia gamma de processos hidrològics, geoquímics i biològics que operen a nombroses escales i donen forma als paisatges, sustenten els ecosistemes i controlen la disponibilitat de recursos. La CZ també és la seu de l'activitat humana i de les infraestructures, per la qual cosa és vulnerable als riscos naturals, com els fenòmens meteorològics extrems, l'activitat volcànica o els terratrèmols. Per això, és fonamental investigar i monitoritzar aquesta capa per comprendre'n la geometria, l'extensió i les propietats físiques per tal d'elaborar avaluacions completes dels perills que podrien produir-se en relació amb aquesta zona tan important.

El sud-est de la Península Ibèrica es caracteritza per una moderada però intensa activitat sísmica que ha causat danys importants des de temps històrics. La sismicitat en aquesta zona es distribueix al llarg d'una banda de deformació relativament àmplia, paral·lela a la costa, formada per un sistema de fallas amb lliscaments ben desenvolupats, coneguda com la Zona de Cisalla Bètica Oriental (ZCBO). L'ZCBO, que discorre al llarg del límit sud de la Depressió del Guadalentí, és una zona densament poblada i amb una gran activitat agrícola. Per tant, l'activitat de les falles a l'ZCBO representa un perill sísmic amb un impacte social i econòmic potencial molt significatiu.

Aquesta memòria es centra en la caracterització de l'estructura i les característiques del subsòl pròxim a la superfície dels sistemes de falles de Carrascoy i Alhama de Múrcia, al SE de la Península Ibèrica. Per aconseguir aquesta caracterització, es van construir diferents models de velocitat-profunditat d'ones de cisalla basats en l'anàlisi multicanal d'ones superficials (MASW). Aquests models també es van combinar amb mètodes de tomografia d'ones P i/o Tomografia de Resistivitat Elèctrica (ERT), així com amb estudis de superfície (per exemple, cartografia geològica i estudi de trinxeres paleosismològiques) com a control, per proporcionar models

millorats del subsòl. Les velocitats de les ones S es van estimar a partir de les ones superficials registrades en les dades sísmiques de reflexió convencionals (font controlada) i la velocitat de les ones P es va determinar a partir de la tomografia de temps de viatge de primeres arribades. El model de velocitat-profunditat resultant va ajudar a determinar els següents punts: i) la identificació de zones de falles poc profundes, incloent una serie de falles cegues desconegudes fins al moment; ii) el gruix de la zona crítica i la seva relació amb les zones de falles a les àrees d'estudi; i iii) proporcionar informació valuosa sobre la xarxa de falles per a les avaluacions de risc sísmic.

La signatura sísmica de les zones de falla, incloses les de les múltiples falles cegues i les zones fracturades identificades als diferents perfils, va quedar ben demostrada mitjançant models de velocitat en profunditat 2D (ones -S i -P). Les firmes sísmiques de les zones de falla i de les falles cegues es caracteritzen per contrastos de baixa velocitat de V_s 500-1000 m/s i V_p 1300-1700 m/s com a conseqüència de la reducció dels mòduls bulk i cisalla al llarg del plans de falla. Els perfils de Carrascoy i La Torrecilla presenten més concentracions de zones de falla que els perfils de La Salut Sud i La Salut Nord, indicant la possibilitat de tractar-se de falles menys madures.

La zona crítica (CZ) es caracteritza per baixes velocitats sísmiques $V_s < 600$ m/s i $V_p < 1300$ m/s, la qual cosa és consistent amb la capa d'alta resistivitat esperada dels sediments al·luvials del Quaternari als perfils de La Torrecilla, La Salut Nord i La Salut Sud, així com la Unitat Roja i l'al·luvial Plistocè-Quaternari al perfil de Carrascoy. L'espessor de la CZ al perfil de La Salut Nord oscil·la entre els 35-45 m i al perfil de La Salut Sud entre els 40-47,5 m. A més, la capa de CZ més gruixuda es descobreix al perfil de La Torrecilla amb un gruix d'uns 40-50 m i la CZ més fina es troba al perfil de Carrascoy amb un gruix d'uns 30-40 m.

A més, els resultats també demostren la relació de les zones de falles actives amb el gruix de la CZ. La presència de falles pot contribuir a la topografia observada de la CZ de dues maneres: canvis en l'elevació del basament rocós com a conseqüència dels canvis a la geometria de les falles

i/o un augment en el nombre de fragments de la capa de regòlit, sent la capa de la CZ prop de la zona de falla relativament més gruixuda que en llocs allunyats de la zona de falla.

La caracterització de les ones de cisalla del subsòl que es presenta en aquest treball proporciona un protocol metodològic i de retroalimentació per estudiar el subsòl suc de les falles actives, complementant els models geològics previs basats en trinxeres paleosismològiques, i, per tant, es poden utilitzar per millorar la avaluació de la perillositat sísmica i l'estudi de les zones crítiques (CZ) d'aquesta i altres regions tectònicament actives del món.

Paraules clau: falla d'Alhama de Múrcia, falla de Carrascoy, zona crítica (CZ), MASW, tomografia d'ones -P, ones superficials

CHAPTER 1

INTRODUCTION

“Science is simply the word to describe a method of organizing our curiosity.”
— *Tim Minchin*

1.1 Active zones and seismic hazard

Collisions between tectonic plates at plate boundaries involve complex deformation mechanisms and associated effects as the growth of volcanic pathways, active fracture zones among other phenomena and structures. Once two (contacting) rock blocks under a stress field suddenly move they generate an earthquake and associated phenomena such as fault activity, energy release etc. The later propagates as seismic waves. There are three types of tectonic plate contacts (Fig.1.1): i) divergent, which are zones where tectonic plates move away from each other; ii) convergent, which are zones where tectonic plates meet; and iii) transform, which are zones where plates move past each other. Along boundaries between tectonic plates network of faults associated with three basic types of faults, i.e normal, reverse, and strike-slip faults develop. Indeed, the characteristics of fault zones (e.g., physical properties) are complex, and sudden movements in fault planes can trigger earthquakes.

Earthquakes can develop into natural disasters that can occur at any time and in any location, and they pose a real threat to our society. Every year, thousands of earthquakes are recorded in various parts of the world, particularly in active zones, which either include both plate tectonic boundaries and areas along the volcanic zones. Broadly speaking, there are three main active zones worldwide [<https://www.usgs.gov>]: i) The circum-Pacific seismic belt (81% of Earth's largest earthquakes occur in this region), this active zone is located along the Pacific Ocean and is often referred to as the Ring of Fire. Earthquakes with magnitudes greater than 9Mw have been recorded in the circum-Pacific seismic belt, including the 9.5Mw Chile (Valdivia Earthquake) in 1960 and the 9.2Mw Alaska Earthquake in 1964; ii) The Alpide earthquake belt, which hosts about 17% of the global cases. This active area stretches from Java to Sumatra in Indonesia, as well as the Himalayas, the Mediterranean, and the Atlantic. The 7.6Mw earthquake in Pakistan in 2005,

which killed more than 80,000 people, and the 9.1Mw earthquake in Banda Aceh (NW Sumatra), Indonesia in 2004, which generated a large tsunami that killed more than 230,000 people, are two of the most devastating earthquakes in this active zone. And iii) the submerged mid-Atlantic Ridge (about ~2%), mostly located in deep water and in remote locations without human infrastructure. Iceland is a well-known example within this area, located just above the Mid-Atlantic Ridge.

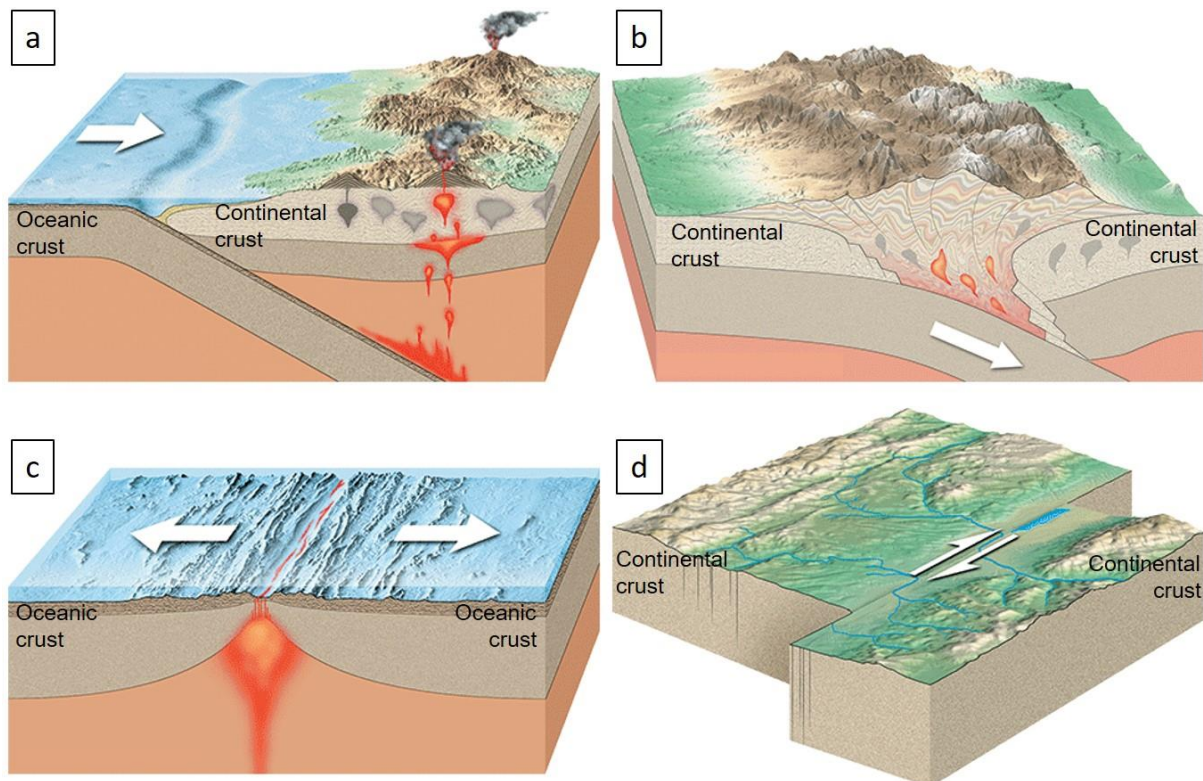


Figure 1.1 The illustration of plate tectonics boundaries. a) the convergent plate boundary of oceanic subduction (oceanic crust subducts beneath the continental crust); b) the convergent plate boundary involving two continental masses, collision between two continental plates; c) the divergent plate boundary; and d) the transform plate boundary [public data access from <https://www.nps.gov>].

According to the most recent earthquake catalog (Fig. 1.2), more than 1000 earthquakes with magnitudes greater than 5 Mw were recorded along active zones around the world from June to December 2021 [Access to public data via <https://erccportal.jrc.ec.europa.eu>]. During this period, for instance, earthquakes with magnitudes greater than 5Mw occurred in Greece (6Mw), Tajikistan (5.8Mw), China (5.4Mw), the Philippines (7.1Mw), Indonesia (5.1 Mw. and 5.5Mw),

Pakistan (5.9Mw), Iran (6.0Mw and 6.3Mw), Haiti (7.2Mw), Peru (7.5Mw), Mexico (7Mw), and Peru (5.8Mw).

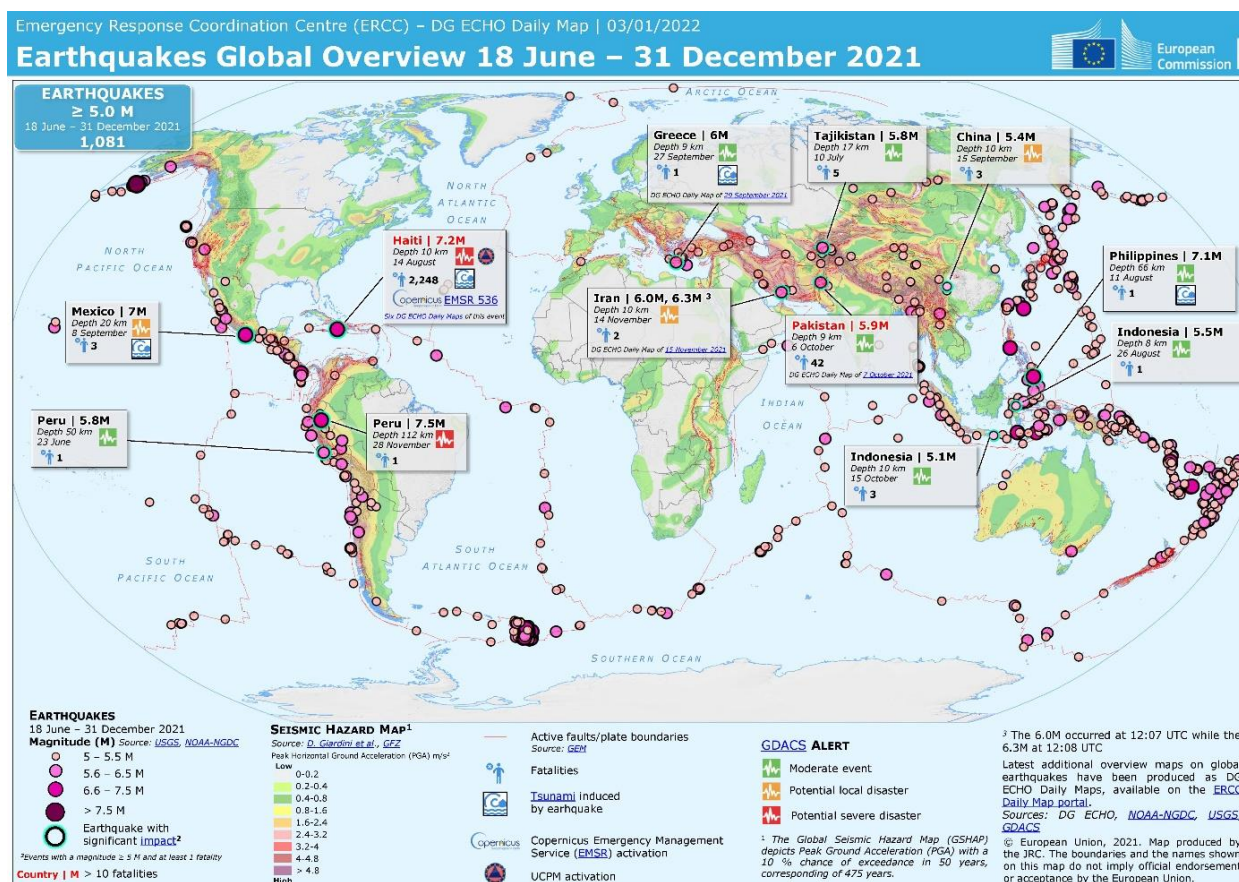


Figure 1.2 The latest global earthquake overview around the world. This data is obtained from recordings in the time interval from June 18 to December 31, 2021 [public data access from <https://erccportal.jrc.ec.europa.eu/>].

Large research effort has been devoted and is currently being carried out in relation to fault zones. The Sant Andreas Fault observatory at Depth (SAFOD) is an outstanding example of this effort [https://earthquake.usgs.gov/learn/parkfield/safod_pbo.php] carried out by the scientific community in USA. Within Europe the Near Fault Observatories (NFO) a thematic core service within EPOS (European Plate Observing System) constitute a long term research infrastructures [<https://www.epos-eu.org/tcs/near-fault-observatories>] that strive to provide multidisciplinary and high-resolution data and high-level scientific products focused on active faults and surrounding areas. Seismicity is mostly associated with deformation bands that include networks of fractures; active faults which control: the architecture, evolution and location of a broad variety of geological

features [Hole et al., 2001, 2006; Bleibinhaus et al., 2007; Zhang et al., 2009; Almeida et al., 2018; Kannaujiva et al., 2021], and they also act as pathways for the migration of fluids [Eberhart-Phillips et al., 1995; Unsworth and Bedrosian 2004; Clair et al., 2019; Paz et al., 2020; Ismail et al., 2020; Li et al. 2022; Liberty et al., 2022]. Furthermore, active fault systems constitute one of the most relevant global geological hazards [Reshetnikoy et al., 2010; Villani et al., 2018; Li et al., 2022]. In general, they can be described as relatively weak zones [Holdsworth et al 2001] featuring complicated geological structures. Along them repeated sequences of displacement movements, often over very long time scales takes place. Therefore, the detailed knowledge of the internal structure of deformation bands along collision zones, and specifically across faults is critical for: hazard assessment, natural resources, hydrological monitoring, for design and development of geological storage facilities; in summary resolving models for the shallow subsurface in this geological environment is a key and critical target to address for basic natural science and Earth system processes.

Thus, this memoir aims to contribute to develop geologic and geophysical models of the shallow subsurface across deformation bands including networks of active fault zones. The studies aim to constrain the fault geometry and produce reliable models for seismic hazard assessments. Seismic hazard assessments attempt to quantify the seismic threats and associated uncertainties in spatial and temporal dimensions to provide estimates for seismic risk and other purposes [Wang, 2011]. Active faults are unique targets for high-resolution seismic imaging techniques due to their tectonic and geodynamic significance [see for example: Hole et al., 2001; Unsworth and Redrosian 2004; Ismail et al., 2020; Paz et al. 2020; Kannaujiya et al., 2021, and references there in]. Seismic methods can detect contrasts in the physical properties [e.g. propagation velocity and density; see for example: Martí et al, 2002a; 2002b; Escuder-Virujete et al., 2003, 2004; Flecha et al., 2004; among others] of and across faults and related damage zones [Martí et al., 2002a, 2002b; Escuder-Virujete et al., 2001; 2003; 2004; Ando and Yamashita 2007, Iacopini et al., 2016]. As a result, seismic methods can help revealing subsurface characteristics, locating fault strands at depth, or

identifying blind faults, allowing to better understand the subsurface structures [Alcalde et al., 2014; Martí et al., 2019; Marzan et al., 2021] and how they accommodate deformation. The detailed analysis of fault attributes and their architecture is thus critical for the characterization of the subsurface [Ercoli et al., 2019] and for improving seismic hazard assessment of active zones.

1.2 The seismicity of the Iberian Peninsula

The Iberian Peninsula lies on the boundary between the Eurasian and African plates, the complex stress distribution has resulted in a continental collision which has contributed to the preset topographic relief, reflected in the Betic, Atlas, Rif orogenic belts., the Gibraltar arc and the Alboran basin [Mezcua et al., 2011; Chertova et al; 2014; Casciello et al., 2015]. The seismicity of the Iberian Peninsula (Fig 1,3) is divided into six main regions [Stich et al., 2020]: i) the Pyrenees, a zone along the Alpine mountains corresponding to the thickened crust along the former plate boundary between Iberia micro-plate and Eurasia; ii) the Iberian Chain, an intraplate between the Western and Eastern domains; iii) Western Iberia; iv) the Southwest-Iberian Margin; v) the Betic Cordillera, the northern branch of the Betic-Rif orogen; and vi) the Alborán Basin, the Betic Cordillera's Eastern segment to offshore deformation in the Alborán Sea. The Eastern Betic Shear Zone (EBSZ) in the Betic Cordillera zone is the most active fault system in the Iberian Peninsula [García-Mayordomo, 2005; García-Mayordomo et al., 2007; Gómez-Novell et al., 2020], and is the focus of this thesis.

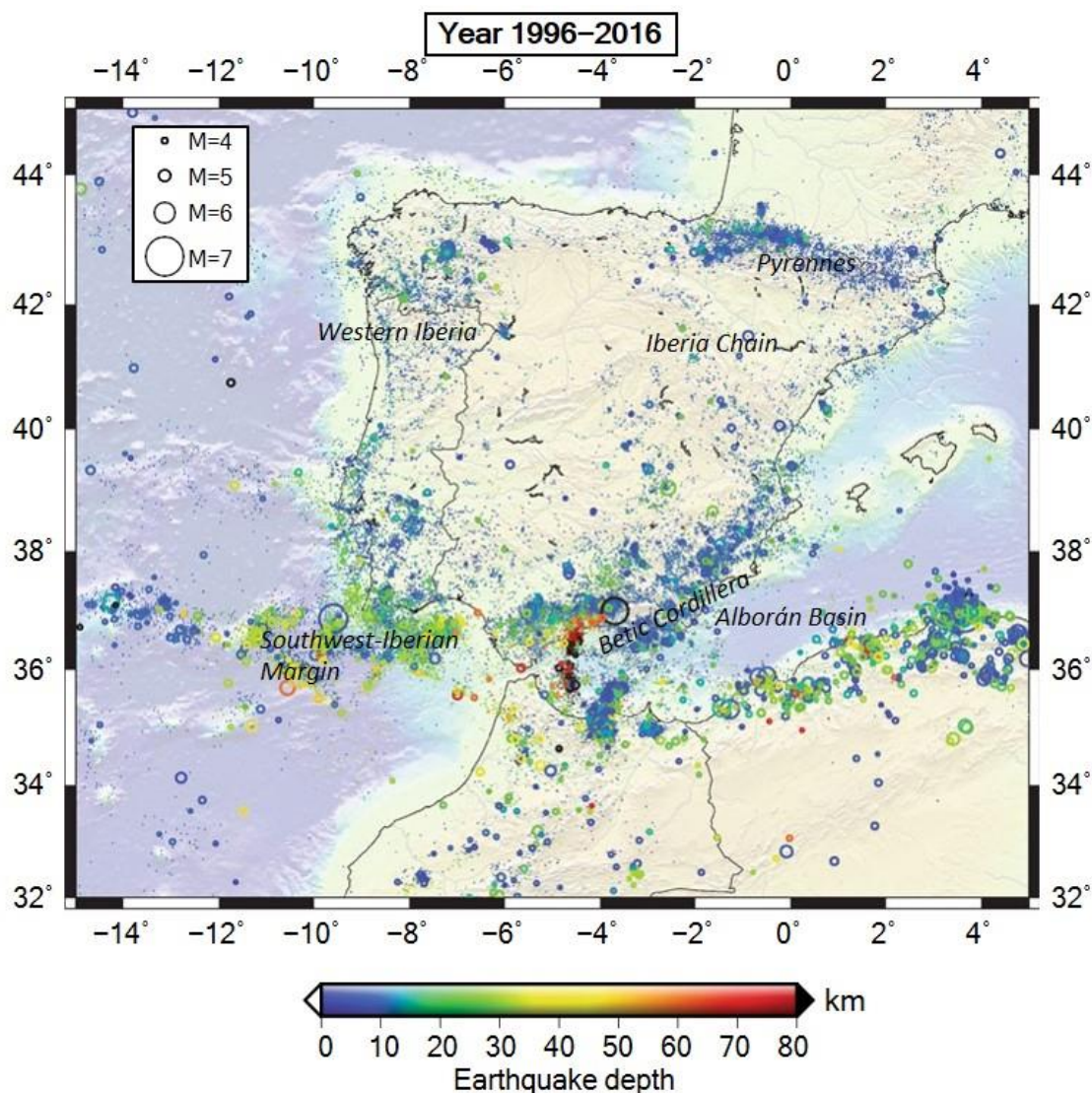


Figure 1.3 Earthquake epicenters in the Iberia Peninsula and surroundings in interval years 1996-2016 [modified from Smith and Sandwell 1997; Becker et al. 2009; Custódio et al 2016; Stich et al, 2020].

1.3 The Eastern Betic Shear Zone (EBSZ)

The Eastern Betic Shear Zone (EBSZ) is a 450-kilometer-long network of NE-SW-oriented faults that stretches from the Alborán Sea to the Mediterranean Sea to the NE of the city of Murcia [de Larouzière et al., 1988; Silva et al., 1993] (Fig. 1.4). The EBSZ system can be considered to be a strike-slip plate boundary, which accommodates part of the convergence within Iberia of the interaction between the Nubian and Eurasian plates [de Larouzière, et al., 1988; DeMets, et al., 1994]. The fault network, fracture system, has reverse and left-lateral strike-slip kinematics with a sigmoidal trend delineated by a number of major individual faults as well as other lower-scale

faults [Visser and Meijninger, 2011; Martínez-Díaz et al., 2012]. The EBSZ is an excellent location for studying the architecture of active faults (Fig. 1.4a, Fig. 1.4b). This area is characterized by intense earthquake activity which has caused significant damage during historical times. Since the early 1990s, several earthquakes have been recorded near the city of Lorca (20km epicentral distance), including Mula in 1999 with a magnitude of 4.7 Mw, Bullas in 2002 with magnitude 5.0 Mw, and La Peca in 2005 with a magnitude of 4.8 Mw [Rodríguez-Escudero et al., 2014]. The maximum intensity observed ranges from VI to VII [Benito et al., 2007].

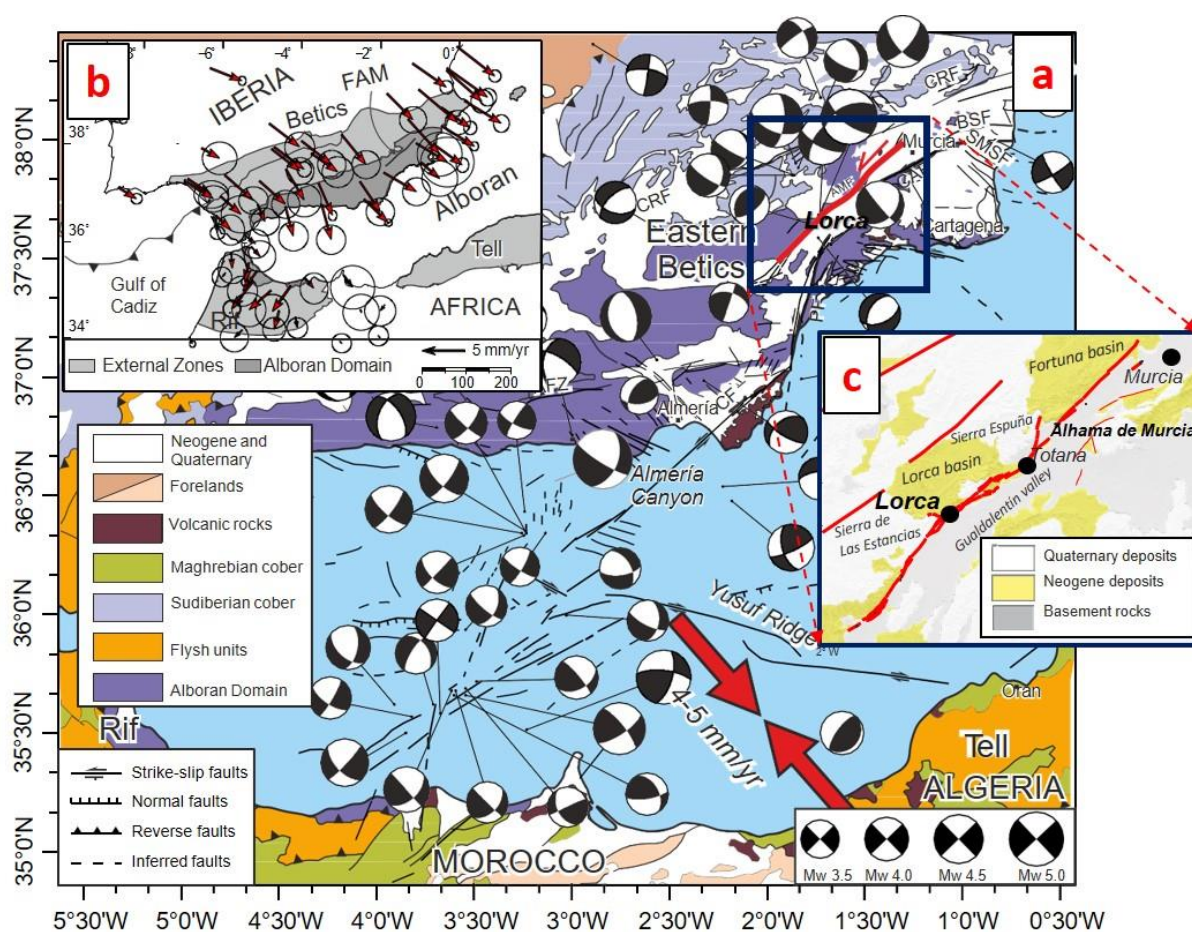


Figure 1.4 The seismicity map around the Iberian Peninsula and study area. a) GPS velocities incorporating the stable Nubian plate [Koulali et al. 2011]; b) The geological map of the area vicinity of the Eastern Betic, Betic Cordillera and the Alborán Basin [IAG, 2011]; and c) The geological plot of the AMF and the Lorca City scenery [modified from Martínez-Díaz et al., 2012].

On May 11, 2011, the most recent and destructive earthquake with magnitude 5.2 Mw struck the city of Lorca. The earthquake caused extensive damage to the city and the surrounding

areas and a few casualties. The earthquake was immediately identified and linked to the Alhama de Murcia fault (AMF) [Vissers and Meijninger, 2011; Martínez-Díaz et al., 2012], an oblique reverse fault that cuts across Lorca and extends for approximately 100km in a NE-SW direction (Fig. 1.4c) [Masana et al., 2004; Sanz de Galdeano et al., 2020]. The official seismic hazard map of Spain, in particular, shows a peak ground acceleration on the rock of 0.23g with a 10% chance of exceeding it in 50 years (475-year return period) [IGN-UPM, 2013].

Since this incident occurred, direct studies to characterize the AMF, primarily from surface and trench observations, have focused on the characterization and determination of fault attributes such as seismic potential and seismic behavior [Ortuño et al., 2012; Martínez-Díaz et al., 2012a; Martínez-Pagán et al., 2018]. However, an analysis of the AMF properties at depth, including the orientation, geometry, physical properties and fault zone configuration of the AMF and its different branches is lacking. The current memoir aims to contribute to the understanding of AMF characteristics, by integrating direct (e.g. outcrop mapping and trench studies) and indirect methods (geophysical methods) to characterize the near-surface expression of the AMF fault and constructing a detailed subsurface geologic and geophysical model.

1.4 Geophysical characterization of the near-surface

To characterize near-surface geological features, high-resolution geophysical methods providing detailed subsurface images are necessary [Martí et al., 2002a, 2019; Alcalde et al., 2014, Ogaya, et al., 2016; Ivandic, et al., 2018; Clair et al., 2019; Lüth et al., 2020; Paz et al., 2020; Gribler et al., 2020; Liberty et al., 2022; among others]. In practice, a high-resolution seismic method (i.e. Multichannel Analysis of Surface Waves, P- wave tomography, etc.) is a well-established technique for investigating the near-surface [Martí et al., 2002a; 2019; Ivanov et al., 2006; Alcalde et al., 2014; Clair et al., 2015; Ogaya, et al., 2016; Ivandic, et al., 2018; Clair et al., 2019; Lüth et al., 2020; Paz et al., 2020; Liberty et al., 2022]. The seismic characterization of the near-surface is a challenging work due to near-surface effects, strong lateral velocity contrasts across steeply dipping structures, presence of soft soils, unconsolidated materials, velocity

inversions and fault-zone heterogeneities [e.g., Impronta and Bruno, 2007; Bruno et al., 2010; Alcalde et al., 2013; Catchings et al., 2014]. Despite these challenges, seismic characterization studies provide extremely valuable information about the shallow subsurface in active tectonic zones, allowing for fault zone characterization, understanding the structural association, mapping the blind fault, mapping the damage zone, imaging the colluvial wedges [Mattson, 2004; Impronta and Bruno, 2007; Villani et al., 2017], and characterizing in detail the Critical Zone (CZ) [e.g., Parsekian et al., 2015; Fan et al., 2020].

Multichannel Analysis of Surface Waves (MASW) is a seismic method developed by Park et al. [1999] to obtain the V_s -depth profile from the inversion process of the surface wave dispersion characteristics. Previous studies using the MASW method have been reported to be successful in characterizing shallow active fault zones: identifying a shallow fault zone and dipping bedrock segments on the Lockatong and Stockton Formations in Kansas (USA) [Ivanov et al., 2006]; characterizing fault avoidance zones and associated geotechnical characteristics on the Springfield Fault, New Zealand [Duffy et al., 2014]; and fault imaging across the Hollywood and Santa Monica Faults, California (USA) [Catchings et al., 2020].

In this memoir, we also used the first arrival P-wave travel time tomography and (Electrical Resistivity Tomography) ERT methods and integrated them with the characterization results from MASW. P-wave tomography is a well-known and extensively used inversion approach to resolve P- wave velocity models aiming to unravel geologic structures [Rohdewald, 2011; Aki & Richards 1980]. The general strategy helps to obtain the most plausible velocity model that can reproduce the observables. This is achieved by minimizing the travel time difference between synthetic or estimated travel times and the real observations (see chapter 3). The theoretical (synthetic) travel times are obtained by simulation using a simple and theoretical model. The ERT technique aims to constrain the electrical properties of the subsurface. Electrical resistivity variations naturally correlate with variations in lithology, water saturation, porosity, and permeability. ERT also can be used to characterize stratigraphic units, structures, fractures, groundwater, and geotechnical

purposes [Griffiths and Barker, 1993; McInnis et al., 2013; Zarroca et al., 2013]. The integration of MASW, P-wave travel time tomography, and ERT methods is an effective strategy for the characterization of the shallow subsurface and model building [Olona et al., 2010; Clair et al., 2015; Place, et al., 2015; Marzan et al., 2021; Flinchum et al., 2022].

1.4.1 The critical zone

The Critical Zone (CZ) is the outermost layer of Earth's surface it includes the air, vegetation (organisms), soil, water, and rock that links the top of the canopy to the bottom of the groundwater (Fig. 1.5) [Chorover et al., 2007]. The CZ is defined as the surface layer of the Earth where interactions occur between the atmosphere, meteoric water, biota life, soil, and bedrock [Brantley et al., 2007]. The CZ extends from the unaltered fresh bedrock to the top of the plant canopy on Earth's surface, also comprises the near-surface aquifers [National Research Council NRC, 2001].

The formation of the CZ is a combination of two important processes, namely: i) soil layer erosion, which can remove weathered materials from the topsoil surface (surface topography), and ii) rock weathering processes, which occur mechanically and chemically and that can break down rock layers separating the underlying bedrock altered and fresh bedrock [Anderson et al., 2004; Anderson et al., 2013; Rempe and Dietrich, 2014]. The collaboration of researchers from different disciplines in studying the characteristics of these complex CZ has resulted in a global network of research platforms that generate knowledge on the CZ in a variety of ecological, geological, and environmental settings [Chorover et al., 2007; Brantley et al., 2017].

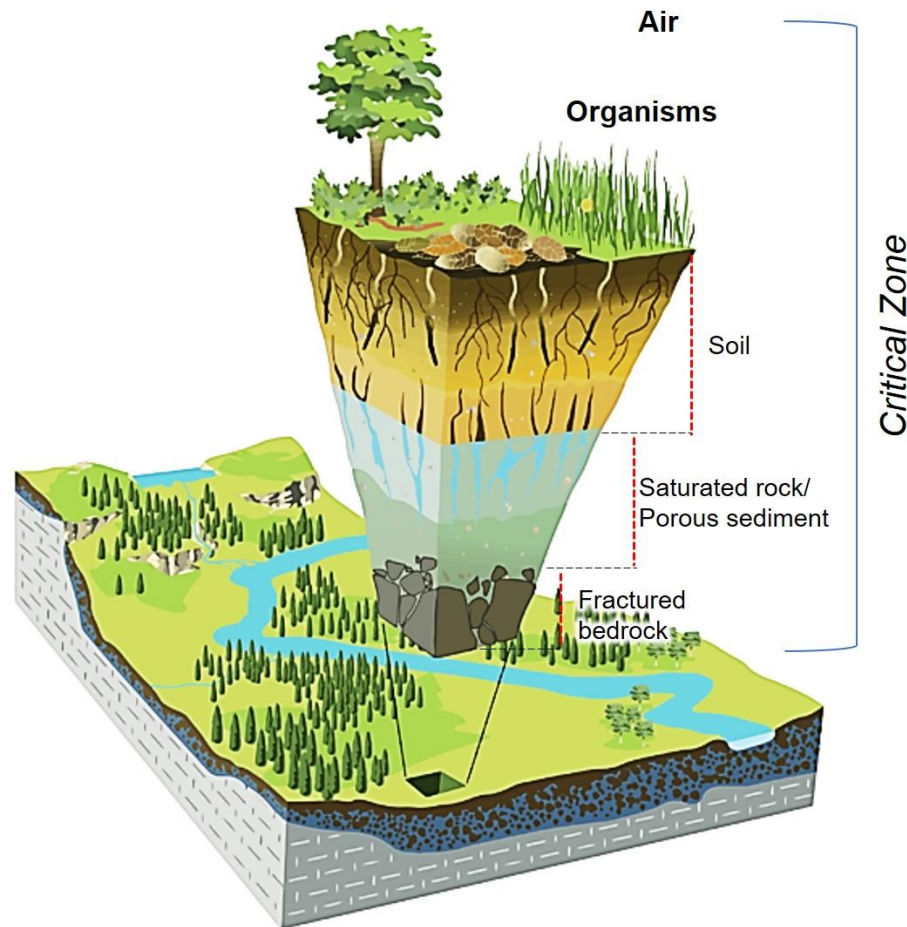


Figure 1.5 The geophysical critical zone target description [modified from Chorover et al., 2007]. CZ is a layer of the Earth's surface consisting of air, living organisms, soil, saturated rock, and fractured bedrock.

The thickness of the CZ can range from 1m to ~200 m, being thicker in mid-latitudes [Xu and Liu, 2017]. Geophysical methods can be used to characterize the geometry and architecture of the CZ, as well as to help predict its maximum depth. The CZ can be divided into three different layers based on geophysical methods, namely topsoil, regolith, and unweathered bedrock (Fig. 1.6) [modified from ISRM, 1981; Schaetzl and Anderson, 2005; Holbrook et al., 2014].

Recent studies on the application of geophysical methods to study the CZ involve several methods, such as the Ground Penetrating Radar (GPR), which uses electromagnetic waves that can show the response of the dielectric properties and permittivity of rocks below the surface; ERT method, which uses electric fields to determine electrical resistivity lithology, fluid content, and subsurface structures; and seismic methods that use elastic properties to reveal seismic velocity

(V_P and V_S) profiles that can be obtained from reflection, refraction, and surface wave methods (as the MASW which is pursued in this memoir) [Parsekian et al., 2015; Clair et al., 2015; Place, et al., 2015; Diane et al., 2021; Flinchum et al., 2022; Trichandi et al., 2022]. The last two (ERT and seismic velocity models) will be used in this work to characterize the thickness of CZ, including the relation to the fault zone, topography, and geological units.

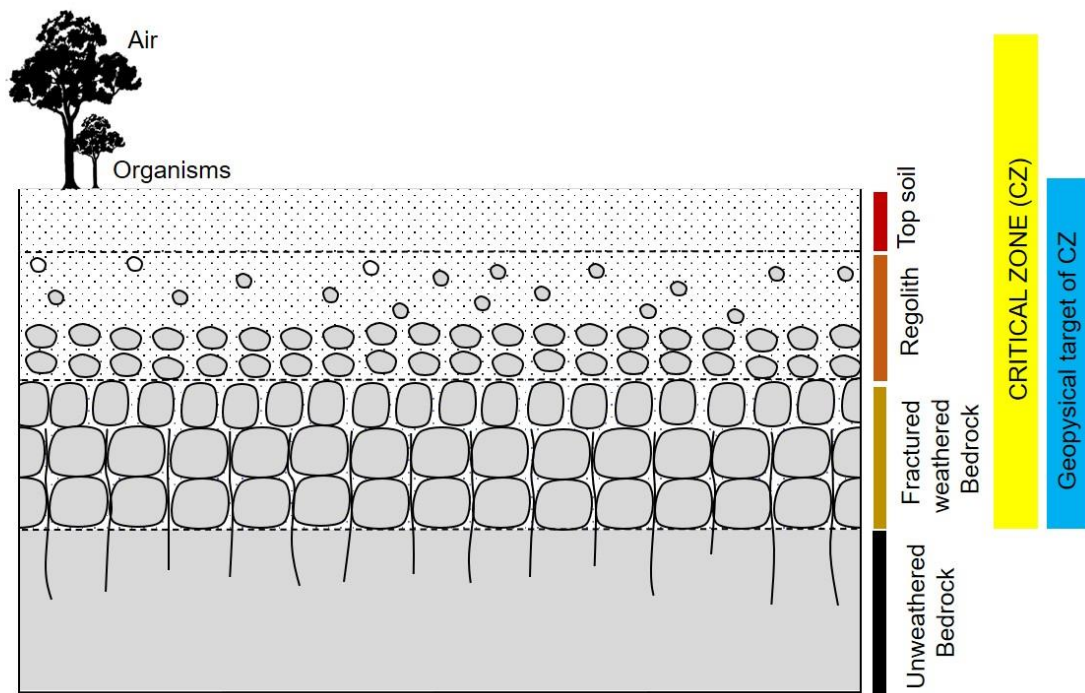


Figure 1.6 Simplified model of the CZ and geophysical target of the CZ depth regarding the weathering profile developed on rock masses [adapted from ISRM, 1981; Schaetzl and Anderson, 2005; Holbrook et al., 2014].

1.4.2 The relationship between CZ and fault zones

Fault zones are areas of extremely high rock complexity with heterogeneous stress-strain distributions at multiple scales. The stress-strain activity of rocks can produce diverse fault geometries at various scales and variable deformation of the surrounding rock layers (e.g. damage zone or fracture networks) [Child et al., 2009]. The fracture network in the bedrock layer can drive the location and extent of weathered zones in the overlying sediment layer, and can sometimes be correlated with the near-surface features. Meanwhile, the presence of faults can potentially lead to: i) a change in bedrock height levels due to changes in fault geometry, or ii) an increase in the

number of altered regolith layer fragments [Clarke and Burbank, 2011; Holbrook et al., 2014; Slim et al., 2014]. Therefore, the presence of fault zones has a strong impact on the thickness and characteristics of the CZ [Mitchell et al., 2019; Moravec et al., 2020; Doser and Baker 2021].

1.4.3 Seismic hazard assessment

The general seismic hazard assessment (SHAs) workflow is shown in Fig. 1.7 [McCalpin, 2009]. Geological and paleoseismic data are used for fault segmentation investigations, recurrence models, prediction of seismic potential, and long-term monitoring of the active area [Wesnousky, 1986; McCalpin, 2009]. In the development of SHAs, probabilistic seismic hazard analysis (PSHA) seismicity studies are also considered [Petersen et al., 2008; Mezcua et al., 2011]. In addition, multidisciplinary studies (e.g. geology, geophysics, and geomorphology) provide strong constraints establishing new assets for SHAs [Reiter, 1990; Wiemer et al., 2009] as well as seismic imaging approaches [Ercoli et al., 2019]. Therefore, in this thesis, we attempt to contribute to the study of SHAs by characterizing especially relevant faults in the area by building 2D physical property models (V_p , V_s and resistivity) of the subsurface across them.

The research carried out to develop this memoir is framed within the data acquired in the INTERGEO project (CGL2013-47412-C2-1-P), funded by the Spanish Ministry of Economy. We focus on the characterization of the structure and nature of the shallow subsurface, including the CZ across a band which is actively being deformed, the EBSZ locates in southeastern Iberia. The target depth to be studied is the shallow subsurface, in the range of 10-200m. The challenges are related to resolution and penetration. For example: the different depths of penetration between the surface studies and, the indirect high-resolution geophysical methods as well as, the integration of the different constrained subsurface models obtained by the different methodological approaches. This integrated effort: a surface geological study of the outcrops and its combination with multiple geophysical methods reduces the level of ambiguity [Place et al., 2015; Clair et al., 2015; Wiederhold et al., 2021]. Further support for the development of this work was provided by the Ministry of Education, Culture, Research and Technology (Directorate General of Higher

Education, Research of Technology of the Republic of Indonesia) providing support for the PhD candidate, author in this memoir. The work carried out and related in this memoir has been presented in a number of international conferences, meetings and workshops, including EGU, EAGE, Deep Earth Exploration and Practices (China), Congreso Geológico de España, and the key outcomes have been published in internationally recognized scientific journals.

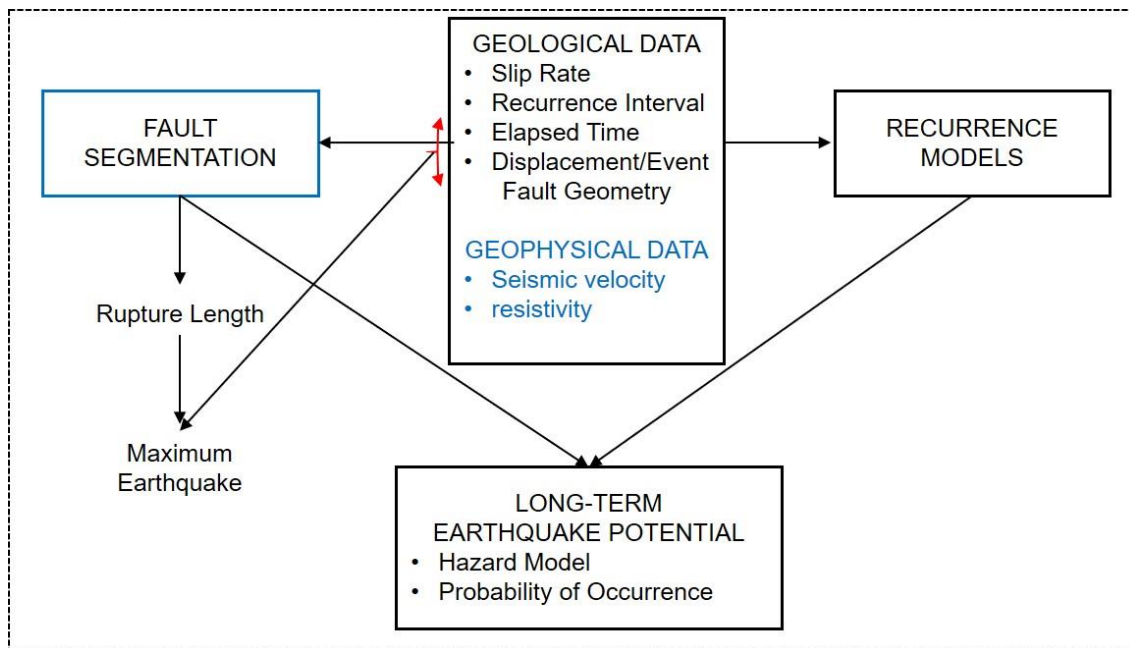


Figure 1.7 The overview of seismic hazard assessment workflow [modified from McCalpin, 2009].

1.5 Objectives of the thesis

The detailed specific objectives of the research carried out and, that are somewhat summarized in this memoir are:

- a. To characterize the shallow subsurface in an area which is actively under deformation which is the area of the Alhama de Murcia Fault (AMF), located in the SE Iberian Peninsula.
- b. Develop a workflow (available through open access) to build 2D Vs seismic velocity models using the MASW method.

- c. Build integrated physical properties models of the shallow subsurface including Vs (derived from MASW), Vp models derived from travel time tomography and resistivity models (from ERT).
- d. Provide an interpretation aiming to unravel the geometry and extend of the identified network of fractures.
- e. Characterize the Critical Zone (CZ) along the EBSZ, unravel the relationship between the fault zone, associated damaged zones and, the thickness of the Critical Zone (CZ).
- f. Deliver the obtained models as a new asset to contribute to seismic hazard assessment, specially in the study area.

To develop this objective a volume of information is required such as: geological and geophysical datasets at different scales, including: surface geologic studies, indirect geophysical datasets consisting on normal incidence seismic reflection data, and ERT. More specifically: i) regional study from the geological maps; ii) local surface geological description of exposed rocks in outcrops, trenches etc, in terms of lithology and fault identification; iii) Surface-wave dispersion analysis of surface wave to obtain a high-resolution Vs-depth models; iv) First arrival travel time data to obtain 2D Vp-depth models through travel time tomography and v) resistivity cross-sections derived from previous ERT surveys.

1.6 Outline of this memoir

This memoir is organized into eight chapters, which are as follows:

- a. Chapter 1 focuses on the general introduction of the study. A brief history and description of seismicity around Lorca City, SE Iberian Peninsula, a definition of CZ, the relationship between geophysical methods and surface data, and the purpose of the research carried out.
- b. Chapter 2 focuses on the geological setting of the study area.

- c. Chapter 3 focuses on basic concepts and methodologies used. The general basic theory of the seismic waves, surface waves, and MASW procedures, generalized inversion and details of the travel time tomography approaches used.
- d. Chapter 4 focuses on the application of MASW in the field datasets, SE Iberian Peninsula (Eastern Betic Shear Zone).
- e. Chapter 5 is the research contribution published in the scientific journal **Geologica Acta, Scopus Q2 (IF: 1.432)**: H. Handoyo, I. DeFelipe, R. Martín-Banda, J. García-Mayordomo, D. Martí, J.J. Martínez-Díaz, J.M. Insua-Arévalo, T. Teixidó, J. Alcalde, I. Palomeras, and R. Carbonell. 2022. *Characterization of the shallow subsurface structure across the Carrascoy Fault System (SE Iberian Peninsula) using P-wave tomography and Multichannel Analysis of Surface Waves*. *Geologica Acta*. Vol. 20 (2022). <https://doi.org/10.1344/GeologicaActa2022.20.9>.
- f. Chapter 6 present the research contribution published in the scientific journal **MDPI Special Issue "Integration of Methods in Applied Geophysics", Scopus Q2 (IF: 2.679)**: Handoyo, H.; Alcalde, J.; DeFelipe, I.; Palomeras, I.; Martín-Banda, R.; García-Mayordomo, J.; Martí, D.; Martínez-Díaz, J.J.; Insua-Arévalo, J.M.; Teixidó, T.; Marzán, I.; Carbonell, R. *Geophysical Imaging of the Critical Zone along the Eastern Betic Shear Zone (EBSZ), SE Iberian Peninsula*. *Appl. Sci.* 2022, 12, 3398. <https://doi.org/10.3390/app12073398>.
- g. Chapter 7 presents the general discussion of the results addressing the contribution to hazard assessment and the characterization of the critical zone CZ.
- h. Chapter 8 summarizes the main conclusions of the research that has been developed.
- i. Reference material used for the research.
- j. Appendix: Abstracts and expanded Abstracts presented in national and international conferences.

1. Paper conference **Near Surface Geoscience Conference & Exhibition Online 2020, EAGE (European Association of Geoscientists & Engineers):** *Handoyo et al., 2020. Multichannel Analysis of Surface Waves (MASW) to Characterize of Fault Zone in Alhama de Murcia Fault.*
2. Poster conference **EGU General Assembly 2021, European Geosciences Union:** *Handoyo et al., 2021. Near Surface High-Resolution Characterization of the Seismogenic Alhama de Murcia Strike-slip Fault.*
3. Paper conference and poster **X Congreso Geológico de España, July 5-7, 2021, Vitoria-Gasteiz, Spain:** *Handoyo et al., 2021. Multichannel Analysis of Surface Wave (MASW) across the Alhama de Murcia Fault Zone: The Case of Fault Structure of La Salud Area.*
4. Poster conference **International Symposium on Deep Earth Exploration and Practices. Nanjing, China 26-31 November 2021:** *Handoyo et al., 2021. Integrated vision of the shallow subsurface in active deformation zone (Lorca, SE Iberian Peninsula).*
5. The scripts of MASW in SU format.
6. Supplementary figures of the results and model interpretations.

CHAPTER 2

GEOLOGICAL SETTING

“Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.”
– Marie Curie

CHAPTER 2

GEOLOGICAL SETTING

2.1 Regional Geology

The EBSZ runs through the Internal Zone of the Betic Cordillera (Fig. 2.1a), which has been hosting the convergence of the Nubian and Eurasian plates since the late Neogene [de Larouzière et al., 1988; DeMets et al., 2015]. The Internal Zone was created by a stack of tectono-metamorphic complexes composed of exhumed Paleozoic, Mesozoic, and Cenozoic rocks [Egeler and Simon, 1969; Azañón et al., 1997]. Former thrusts were reactivated as low-angle normal faults as extensional tectonics associated to the South Balearic basin continued until the middle Miocene (Serravalian) [e.g., Sanz de Galdeano, 1990; Azañón and Crespo-Blanc, 2000].

Partially concurrent with this extension (from the Langhian to the Messinian), intense magmatic activity occurred in this area [López Ruiz et al., 2004], and Neogene sedimentary basins (e.g., Lorca and Fortuna basins) were formed [Montenat et al., 1987]. The tectonic setting (strike-slip faults) of the Nubian and Eurasian plates, from the late Messinian to the beginning of the Pliocene [de Larouzière et al., 1988; Khazaradze et al., 2008; Echeverría et al., 2011; DeMets et al., 2015] inverted previous Neogene basins, and the formed in an area that was previously uplifted. Moreover, the NNW-SSE regional shortening orientation has remained consistent in the region from the late Miocene [Martínez-Díaz, 2002] to present, as proven by magnetic polarities [e.g., De Mets et al., 2015] and GPS tools [Argus et al., 2010].

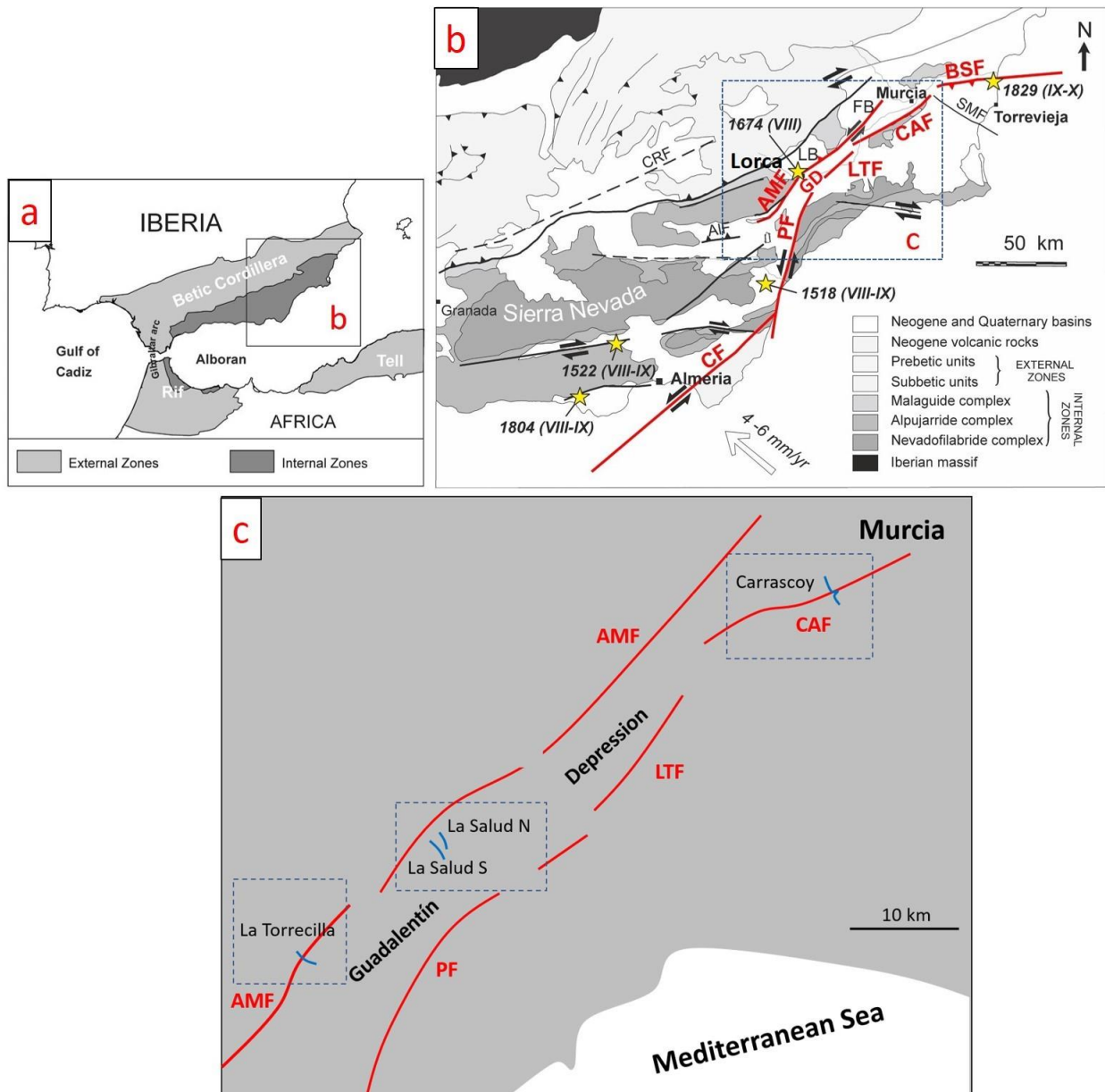


Figure 2.1 a) Geodynamic setting and location of the EBSZ within the Iberian Peninsula; and b) Geological map of south-eastern Spain, where the deformation corridor of the EBSZ is located, with the main active faults identified (red-lines) [Modified from Ortuño et al., 2012; Gómez-Navel, 2021; Marín-Lechado et al., 2011]. Yellow stars indicate the most relevant historical earthquakes. BSF: Bajo Segura Fault; CAF: Carrascoy Fault; LTF: Los Tollos Fault; AMF: Alhama de Murcia Fault; PF: Palomares Fault; and CF: Carboneras Fault. Furthermore, LB: Lorca Basin; FB: Fortuna Basin; and GD: Guadalentín Depression. c) Simplification of the basemap of the research area. The seismic profile consists of four lines: La Torrecilla, La Salud North, La Salud South and Carrascoy.

The study area lies within the EBSZ central and northern regions (Fig. 2.1b). The Guadalentín Depression is delimited by the Alhama de Murcia Fault (AMF) to the north and by the Carrascoy fault system (CAF) to the south. The AMF is split into four sections based on geomorphological expression, seismicity rate, and fault zone geometry [Martínez-Díaz et al., 2012a], that run from SW to NE: i) Góñar-Lorca, a narrow N40E fault zone that ends in horsetail to the south; ii) Lorca-Totana, a section with a N60E trend and a 2km wide fault zone where Gómez-Novell et al. [2020] describes more than five strands; iii) Totana-Alhama de Murcia, which recovers the N40E trend which controlled the evolution of the Fortuna basin to the NW but shows low geomorphologic fault expression. The CAF takes control the accommodation of the convergence from the Alhama de Murcia fault toward the NE [Martínez-Díaz et al., 2012a; Martín-Banda et al., 2016].

2.2 The study area

One of the most prominent and active regions in the Internal Zones of Betic Cordillera is the Eastern Betics Shear Zone (EBSZ) [Bousquet, 1979; De Larouzière et al., 1988; Sanz de Galdeano et al., 2019], which is the focus of the present study. The study area has been investigated through four seismic transects that sample different portions of the AMF-CAF fault system: (1) La Torrecilla, (2) La Salud North, (3) La Salud South, and (4) Carrascoy (simplification sketched in Fig. 2.1c). The local geology found in the four transects is described below.

2.2.1 La Torrecilla

The La Torrecilla profile is located in the northern segment of the AMF Góñar-Lorca section (Fig. 2.2). The area includes metamorphic rocks that are separated from the Quaternary deposits of the Guadalentín Depression by a single strand and a 100m wide deformation shear zone. The Góñar-Lorca shear zone covers deformed Upper Miocene materials (marls, sandstones, and conglomerates) as well as a 20m in width band of fault gouge involving the Alpujárride and Maláguide Complexes (phyllites, quartzites, and schists) [Martínez-Díaz et al., 2018]. To observe recent AMF events, excavation of several trenches at the bottom of La Torrecilla Creek has

provided information that the fault zone is covered by very recent fluvial sediments [Martínez-Díaz et al., 2016]. This fluvial sediment layer was discovered on the southeastern edge of the shear zone during excavations.

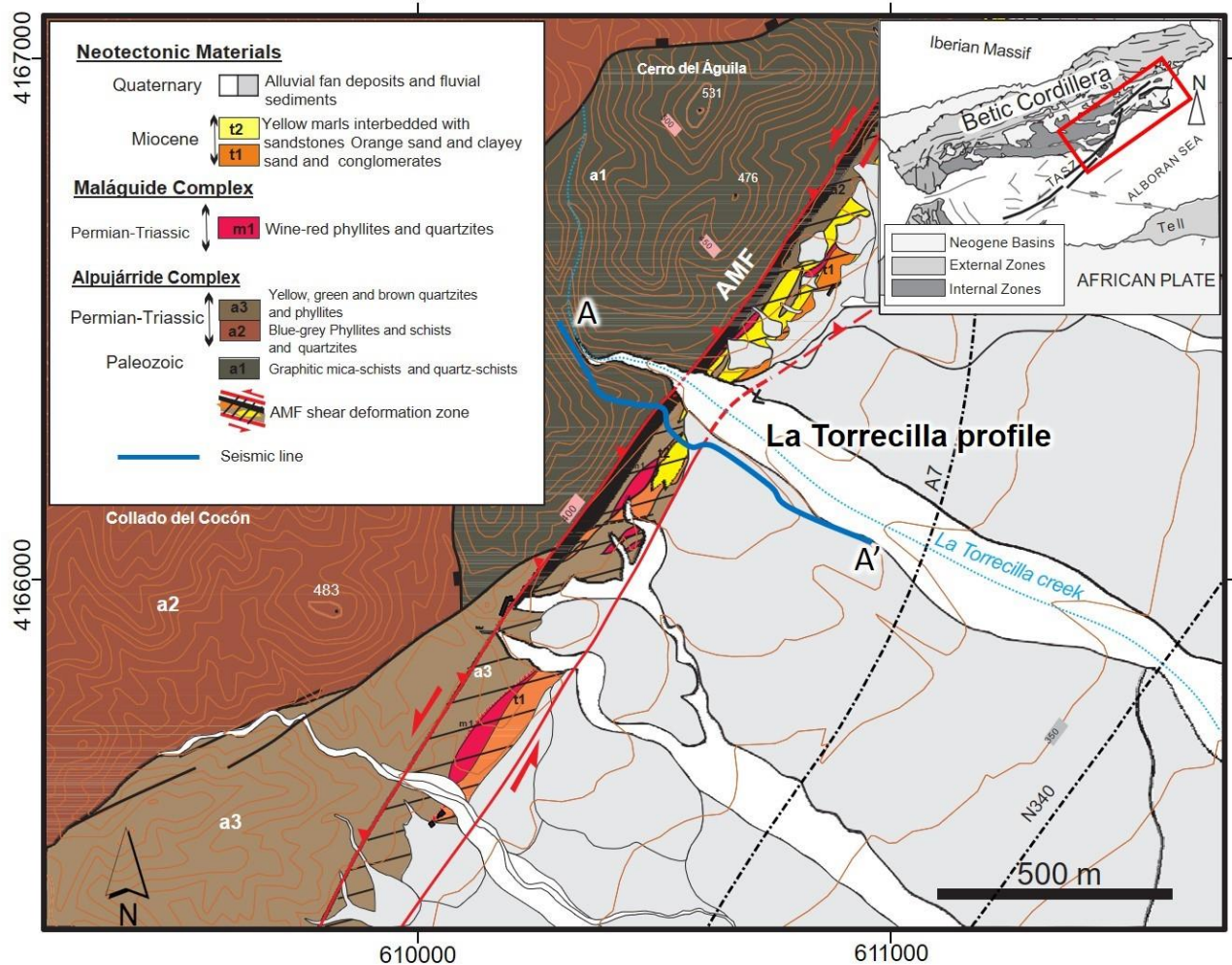


Figure 2.2 Geological setting of the La Torrecilla site [modified from Martínez-Díaz et al., 2018; Gómez-Novel, 2021].

The La Torrecilla area includes the following geological units [Gómez-Novel, 2021] (Fig. 2.2): i) Paleozoic: Graphitic mica-schists and quartz-schists; ii) Permian-Triassic: Yellow-green-brown quartzites, phyllites, Blue-grey phyllites, schists, and quartzites; iii) Permian-Triassic: Wine-red phyllites and quartzites; iv) Miocene: Yellow marls interbedded with sandstones, orange sand, clayey-sand, and conglomerates; and v) Quaternary: Alluvial fan deposits and fluvial sediments.

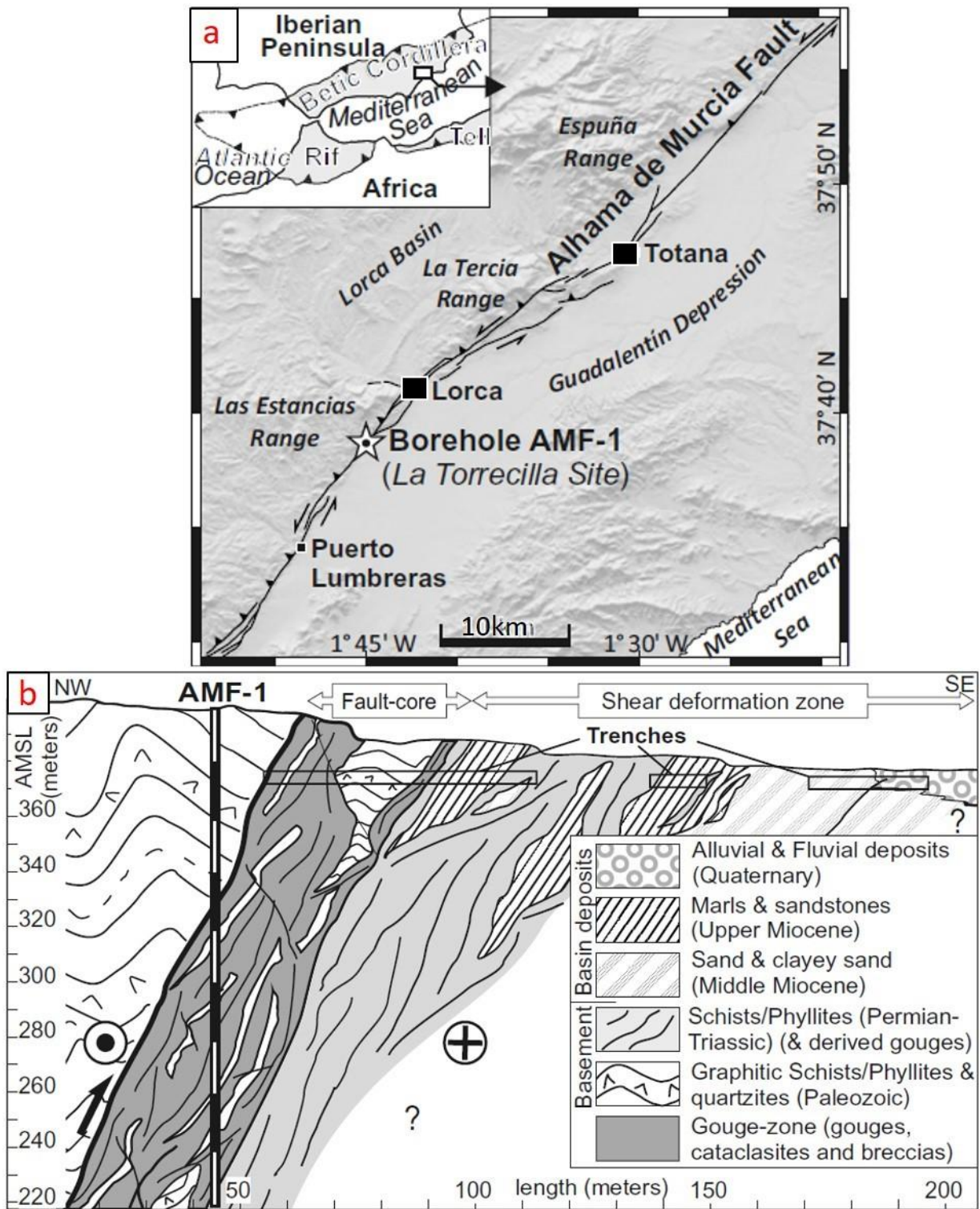


Figure 2.3 a) The map of Alhama de Murcia Fault, in the La Torrecilla site. b) The schematic of cross-section of fault zone in borehole AMF1, which is located at 37.638°N, 1.746°W. AMSL: above mean sea level [modified from Rodríguez- Escudero, 2017; Rodríguez- Escudero et al., 2020].

Several outcrops were used for structural studies and sample collection in the surface and/or near surface, specifically the La Torrecilla Creek portion in which the AMF is exceptionally well preserved (Fig. 1a). A borehole (AMF-1) was created at this location by drilling through the fault-core rocks and hanging wall [Martínez-Díaz et al., 2016]. Moreover, trenches were excavated in the AMF fault plane to produce a continuous and fresh fault zone exposure. Surface study observation, drill-core analysis, and geophysical investigation revealed structural evidence for an asymmetric fault zone at the surface [Martínez-Díaz et al., 2016; Martí et al., 2016; 2020]. At this location, most of the strain is accommodated by the fault core gouge zone on the NW of the fault (Fig. 1b). Due to the folding and uplift of the Las Estancias and La Tercia ranges, the fault zone in the SE direction comprises a shear zone in sharp contact with the fault core, including the uppermost tectono-stratigraphic unit [Rodríguez-Escudero, 2017; Rodríguez-Escudero et al., 2020].

2.2.2 La Salud North and La Salud South

The La Salud North and South profiles are located in the center of the Lorca-Totana section of the AMF (Fig. 2.4). In this sector, the fault affects the Neogene sedimentary rocks from the Guadalentín Depression (mainly marls and gypsums) and the Paleozoic rocks from the Alborán Domain (phyllites, quartzites and schists). The youngest sediments in most of the AMF study areas (La Salud North and La Salud South) are mostly Plio-Quaternary old alluvial fan facies that drain the main deposits in the area to the Guadalentín Depression in the central region and Huercal-Overa in the south [Ferrater et al., 2017].

The primary kinematics of the Lorca-Totana segment of the AMF is strike slip with reverse component (oblique-reverse), which is the liable for the uplift of the La Tercia range. The strong reverse component of this fault segment has been interpreted as a result of its ENE-WSW orientation with respect to the regional NNW-SSE compression area [e.g., Martínez-Díaz et al., 2012b]. This set of faults are considered to be the core of a strike-slip shear fracture system, being the AMF the main structural feature. The shear zone is a ~1km wide deformation zone that contains

sets of faults with NW-SE and SW-NE directions [Martínez-Díaz et al., 2012a; Martínez-Díaz et al., 2012b]. The Lorca-Totana segment exhibits one of the most prominent surface expressions (deformation zone) entire the fault zone, which is motivated the development of most of the paleoseismic studies available so far in the EBSZ [e.g., Silva et al., 1997; Martínez-Díaz et al., 2003; Masana et al., 2004; Ferrater, 2016; Ferrater et al., 2017].

The La Salud South profile runs through the two southernmost strands (S-AMF) and the frontal branch (F-AMF), from the four identified in this section [e.g. Martínez-Díaz et al., 2002; Masana et al., 2004; Gómez-Novell, 2021]. Meanwhile, The La Salud North profile does not reach the southernmost strand (F-AMF) but it does in the central strand (S-AMF) [Gómez-Novell, 2021].

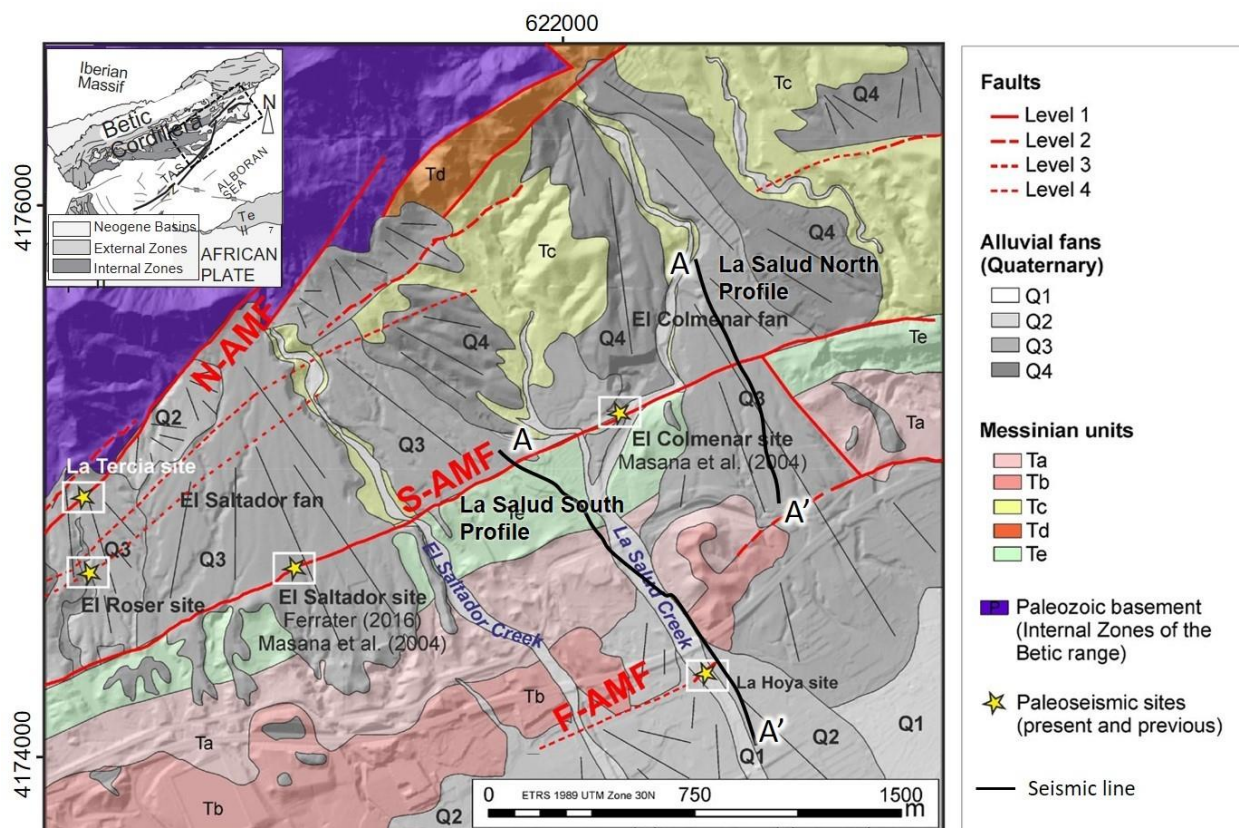


Figure 2.4 Geological setting of the La Salud North and La Salud South profiles [modified from Ferrater et al., 2017; Gómez-Novell, 2021].

2.2.3 Carrascoy

The Carrascoy (CAF) system (Fig.2.5) is formed by two overlapping segments, with different geometrical, structural and kinematic characteristics [Martín-Banda et al., 2016]. The NE domain extends ~16km to a N50E trend between Los Ramos and El Palmar villages and controls the location of the Cresta del Gallo Range. The SW segment is more complex, represented by: i) the CAF *sensu lato*, that uplifted the Carrascoy Range, and ii) the Algezares-Casas Nuevas fault (ACNF), that runs for ~23km from the villages of Algezares to Casas Nuevas. The CAF system is a sub-vertical fault with a general left-lateral strike-slip kinematics. Towards its SW part, the ACNF develops as a low-angle oblique reverse fault [Martín-Banda et al., 2016].

The surface geology and the information derived from geomorphological mapping, morphotectonic analysis and paleoseismological trenches performed along the CAF domain, revealed the growth of a fold-and-thrust belt related to the ACNF and transported to the north since 209.1 ± 6.2 ka [Martín-Banda et al., 2016; Martín-Banda, 2020; Martín-Banda et al., 2021]. The ACNF constitutes the currently active front of the Carrascoy Range whose development progressively moves to the NW [Martín-Banda et al., 2016] forming a fault propagation anticline.

The oldest rocks cropping out in the study area correspond to the metamorphic basement of the Alborán Domain, located in the highest part of the Carrascoy Range. Towards the south of the Alboran Domain, upper Miocene marine sedimentary rocks (marl, biocalcarene and limestone) crop out divided into two units of Tortonian and Messinian ages. Along and parallel to the ACNF, a band of Pliocene-middle Pleistocene continental deposits (conglomerate, gravel, sand, marl, and limestone) is deformed in the hanging wall of this fault.

These Pliocene-middle Pleistocene deposits are locally known as the Unidad Roja (Red Unit) [Jerez et al., 2015] and are considered to be older alluvial fans coming from the erosion of the higher parts of the Carrascoy Range. The youngest materials are middle Pleistocene to Holocene alluvial deposits that fill the Guadalentín Depression. They were accumulated during five generations of alluvial fan systems, intercalated with valley floor deposits, glaciais and

endorheic deposits [e.g., Martín-Banda et al., 2016], demonstrating the transition from alluvial to fluvial sedimentary systems [Silva, 2014].

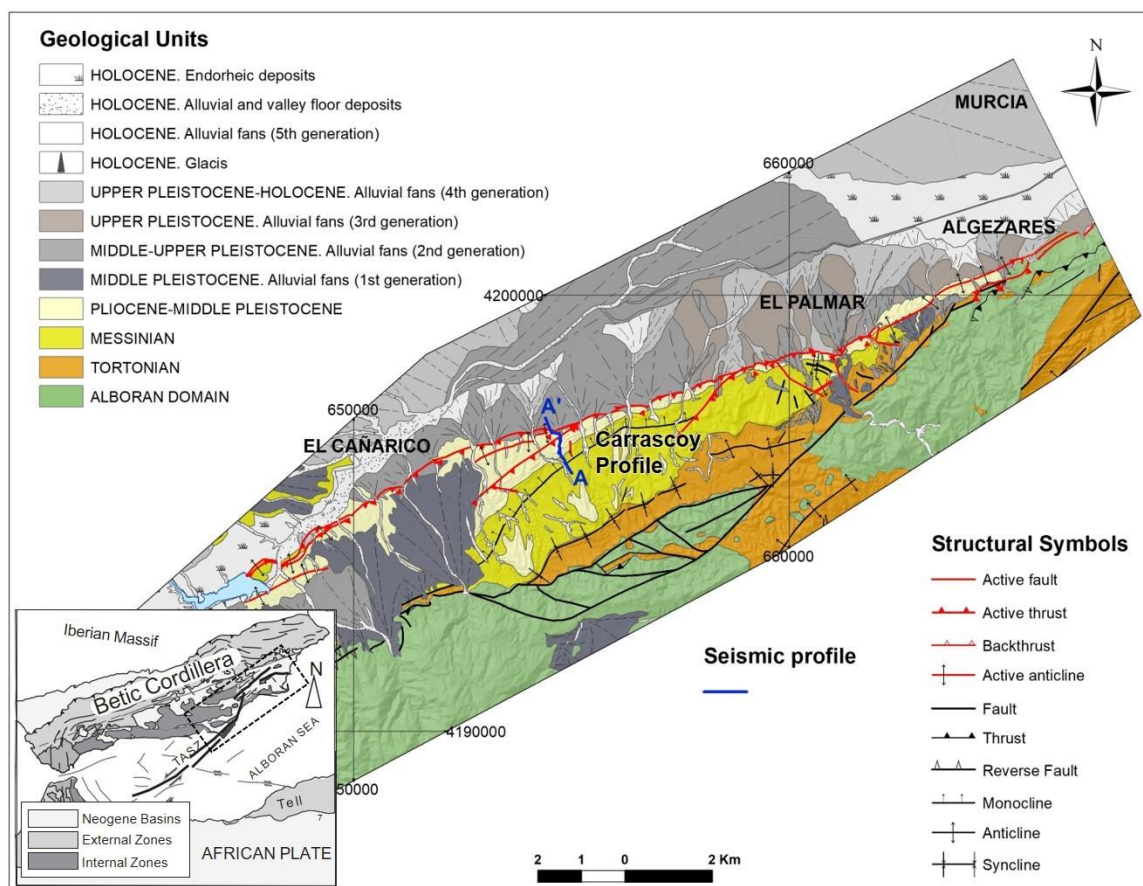


Figure 2.5 Geological setting of the Carrascoy profile and the Algezares-Casas Nuevas Fault [modified from Martín-Banda et al., 2016].

CHAPTER 3

METHODOLOGY

“Science is not only a disciple of reason but also one of romance and passion.”
– Stephen Hawking

The main objective of this memoir is the characterization of the shallow subsurface in the neighborhood of an active fault and, unravel the fine structure, configuration and the distribution of the physical properties of the critical zone (CZ) in the SE Iberian Peninsula. In this thesis, the methods used include: MASW and P-wave travel time tomography. This chapter consists of two sections: i) Some theoretical background on seismic waves and ii) the Multichannel Analysis of Surface Waves (MASW) procedure.

3.1 Some theoretical background on seismic waves

Seismic exploration is one of the most popular geophysical techniques, thanks to its resolution power that allows to resolve both large- and small-scale subsurface features. In simple terms, the seismic approach uses the return (upcoming) seismic waves that have traveled through the Earth to estimate the form and physical characteristics of the rocks in the subsurface. Like many other geophysical prospecting techniques, seismic imaging was conceived and developed for the exploration of oil and gas resources. Early on in the history of hydrocarbon exploration, oil was found by drilling large scale folds (anticlines) in exposed rock and oil seeps. Geologists then used seismic surveys to look for deeper, less obvious oil and gas traps. Once seismic images were acquired, and geologically interpreted drilling of conspicuous structures was carried out. In 1924, seismic data was employed for the first time in the discovering of an oil field in Texas [Milligan, 2004]. The fundamentals of seismic data acquisition, processing, and interpretation are covered in a number of introductory and advanced textbooks including: Telford et al. [1990], Sheriff and Geldart [1995], and Yilmaz [2001] (as well as in references therein).

Seismic methods are remarkably suitable for studying the Earth's interior and its structures. Seismic waves are naturally triggered by tectonic plate activity (e.g. by earthquakes), as well as by volcanic eruptions, landslides, or human activity. Seismic source at any point on the Earth

generates four types of seismic waves: compressional (P- waves), shear (S- waves), Rayleigh waves (known as ground-roll in reflection seismic exploration) and Love waves [Aki & Richards, 2002]. Once there is a seismic disturbance in the Earth, the energy produced propagates in the form of these waves transmitted within the subsurface and along its surface.

The rocks that form the subsurface of the Earth feature different physical properties, elastic moduli, density; P and S wave propagation velocities. Because P- and S- waves spread outward in all directions from the seismic source and, travel through the Earth's interior, they are also known as body waves and, are the key players in seismic exploration. On the other hand, Rayleigh and Love waves propagate along layers near the surface and are, therefore, known as surface waves. The depth penetration of surface wave surface is a function of its characteristic wave-length. Therefore, only very long wave-length can sample deep levels within the Earth and their application in oil and gas exploration is thus rather limited [Aki & Richards, 2002; Mondol, 2010] due to the lack of resolution.

3.1.1 Body Waves

Body waves consist of compressional waves (P- wave) and shear waves (S- wave) that are transmitted through the medium of the Earth's interior. As shown in Fig. 3.1a, the particle motion travels parallel to the wave motion in the compressional waves, allowing stretching and compression of elementary volume, culminating in shape change. Shear wave particle motion, on the other hand, is perpendicular to wave propagation and thus has vertical and two horizontal components. In Fig. 3.1b, the shear deformation of elementary volumes within the medium is driven by transverse particle motion [Bolt, 1976; Aki & Richards, 2002; Evrett, 2013].

P- and S- waves have distinct characteristics that can reveal information about the internal physical properties (e.g. elastic moduli, V_p , V_s , and density) of the medium through which they propagate. These characteristics are a consequence of the mineral composition of the medium and also of other complex properties such as structure, fluid content, porosity, permeability, etc.

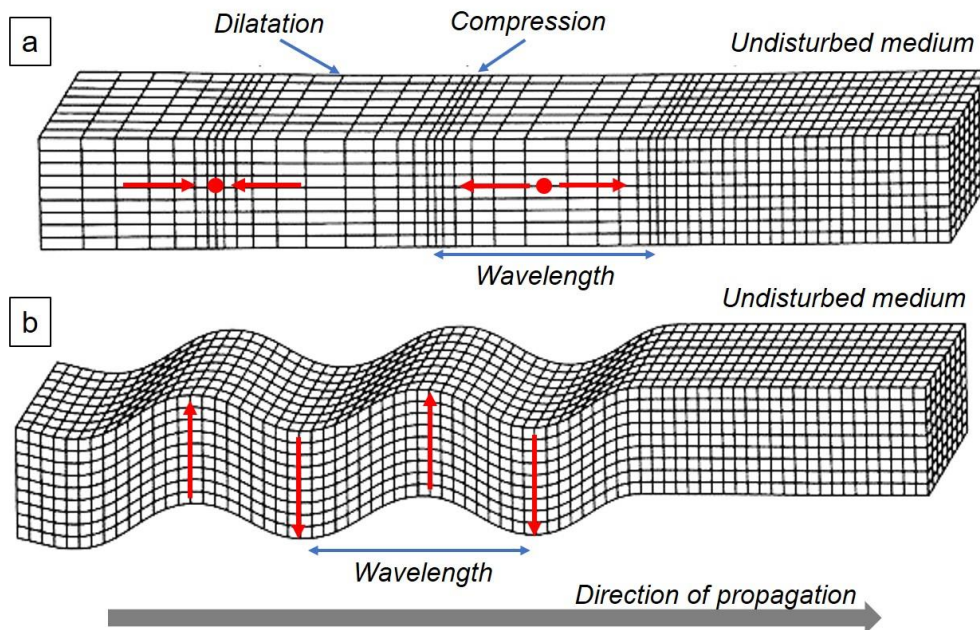


Figure 3.1 The type of seismic waves: (a) The particle displacement is related to P- waves and (b) the particle motion affiliated with S- waves [modified from Bolt, 1976].

3.1.2 Surface Waves

Surface waves transmit through near-surface layers. Rayleigh waves exhibit elliptical motion in the plane perpendicular containing the wave propagation direction (Fig. 3.2a), whereas Love waves exhibit transverse motion (Fig. 3.2b) [Aki & Richards, 2002; Evrett, 2013].

a. Rayleigh Waves

Rayleigh waves are the most frequently used surface waves in near-surface geophysical exploration. Rayleigh waves (also known as ground roll in control source seismic data acquisition), have a remarkably high-amplitude, low-frequency and low group velocity, and they travel along or very close to the Earth's surface [Park et al., 1998; Aki & Richards, 2002; Evrett, 2013].

Rayleigh waves are produced by intermediate surface particles moving in a vertical plane along elliptical paths in the direction of displacement. Near the surface, particle motion takes the shape of a retrograde, which transitions to a prograde as depth increases (Fig. 3.3b) [Aki & Richards, 2002; Evrett, 2013]. In homogeneous media, the amplitude decreases (less than 30% of its surface value) with depth, becomes negligible within about a wavelength (λ) of the surface [Fig. 3.3(a)]. At the point source, the energy of the waves is proportional to $1/r$ (being r is the distance

to the source), therefore the amplitude in the plane-wave decreases as $1/\sqrt{r}$ [Young & Freedman, 2008; Evrett, 2013].

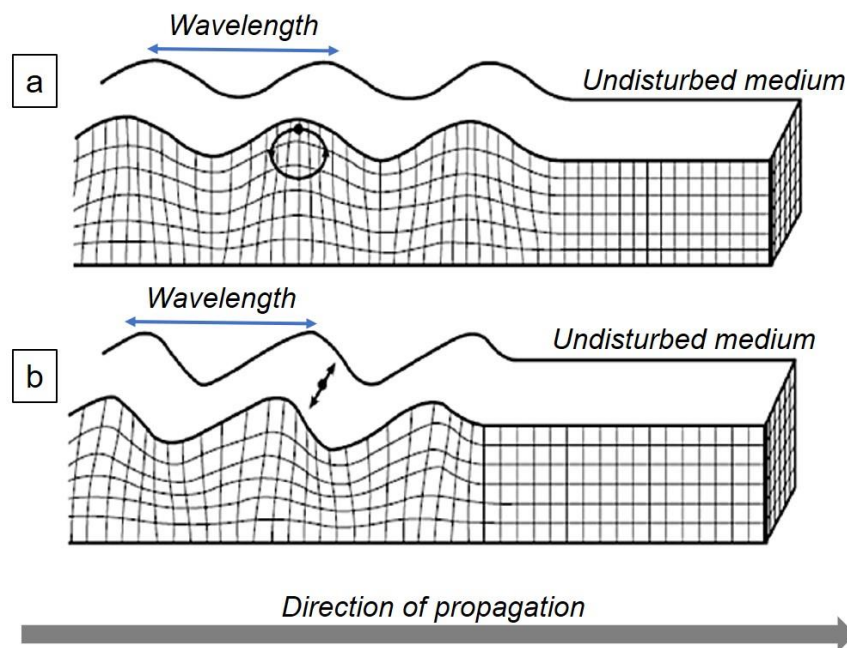


Figure 3.2 Particle motion produce by (a) Rayleigh waves and (b) Love waves [modified from Bolt, 1976].

Ground roll is the most prevailing type of surface wave recorded in control source seismic data [Park et al., 1998; Xia et al., 1999]. Vertical seismic sources (e.g. sledgehammers, vibrating plates, and accelerated weight-drop) will produce a group of P-, S-, and Rayleigh waves, with approximately 67% (two-thirds) of seismic energy transmitted in the form of Rayleigh waves (mainly ground roll), while 23% is to the S- waves and 7% to the P- waves [Evrett, 2013]. Love waves (around 3% of seismic energy transmitted) are rarely detected in surveys using vertical sources and vertical receivers due to their horizontal particle motion [Park et al., 1997; 1998].

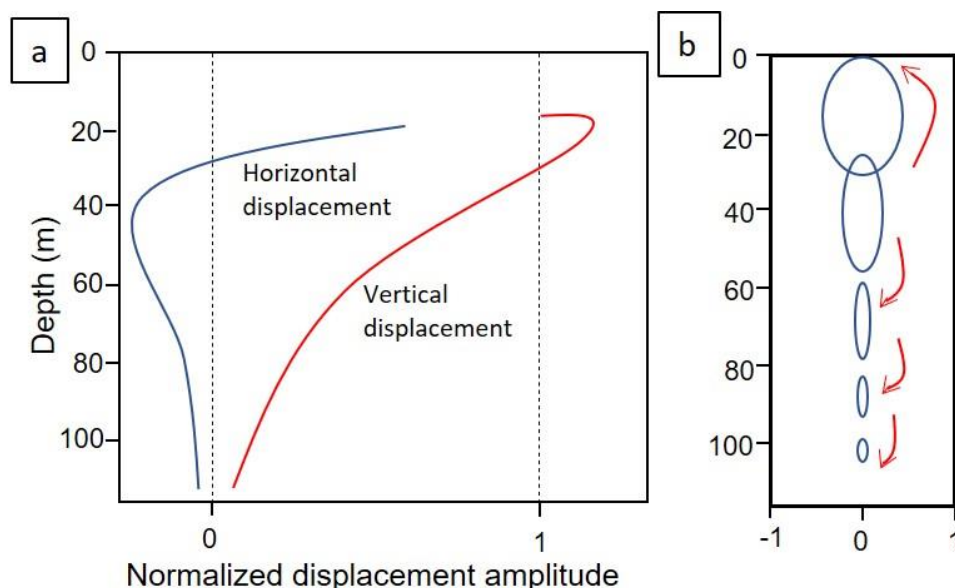


Figure 3.3 (a) Illustration of displacement amplitude and (b) Vertical particle movement of Rayleigh waves on a depth profile [modified from Gedge & Hill, 2012].

Rayleigh waves do not get dispersed in homogeneous half-space media since their velocity in a homogeneous half-space is independent of the frequency. However, Rayleigh waves are dispersive in stratified media, which means that waves with different wavelengths (λ) and frequencies (f) travel at different speeds through the depths' boundaries. The velocity at which a single frequency propagates is called the phase velocity (V_{ph}), while the velocity at which the envelope of group of waves propagates through the medium is the group velocity (V_g) [Park et al., 1998; Evrett, 2013]. In Fig. 3.4, the blue dot propagates along the black path at the phase velocity, while the red wave-packet envelope moves from left to right at the group velocity. Rayleigh wave dispersion can be visualized by evaluating an ideal seismic source, which vibrates at a single frequency on the surface of a multi-layered elastic medium. Rayleigh waves have a constant wavelength that can be determined by measuring the distance between two peaks or troughs from the observed data. Low-frequency sources produce Rayleigh waves with long wavelengths that can reach deeper layers (multiple layers), while high-frequency seismic sources produce shorter wavelengths which are confined to shallower penetration depths (Fig. 3.5) [adapted from Foti et al., 2015].

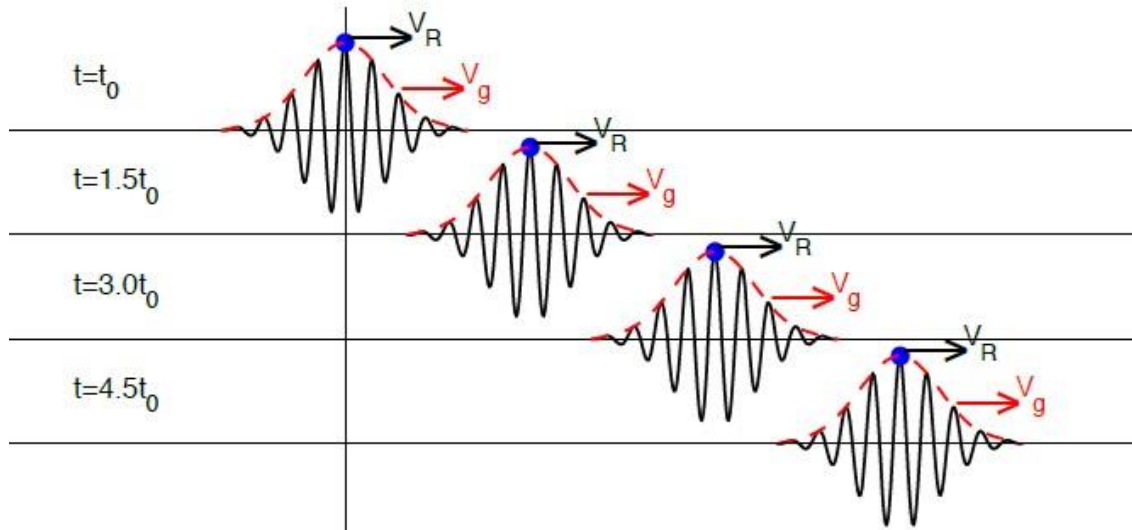


Figure 3.4 Illustration of the difference between Rayleigh wave phase velocity (V_R) and group velocity (V_g) [adapted from Everett, 2013]. The blue dot propagates at phase velocity, while the red line represents the velocity of a wave packet.

The phase velocity of each wave component depends mainly on the elastic modulus of the layer through which the wave travels. In Fig. 3.5a, the phase velocity of the Rayleigh waves (V_R) is only affected by the elastic modulus of the uppermost layer, while the phase velocity of the wave in Fig. 3.5b also depends on the elastic properties of the deeper layers. Therefore, each particular surface wave mode will exhibit a specific phase velocity at each frequency [Xia et al., 2002]. In general, seismic velocity increases with depth, implying that longer wavelengths propagate faster than shorter wavelengths, as shown by:

$$\lambda(f) = \frac{V_R(f)}{f} \quad (\text{Eq. 3.1})$$

where f is frequency, $V_R(f)$ is the phase velocity of Rayleigh waves at a frequency f and $\lambda(f)$ is the Rayleigh waves wavelength at a frequency f [Bessason & Erlingsson, 2011].

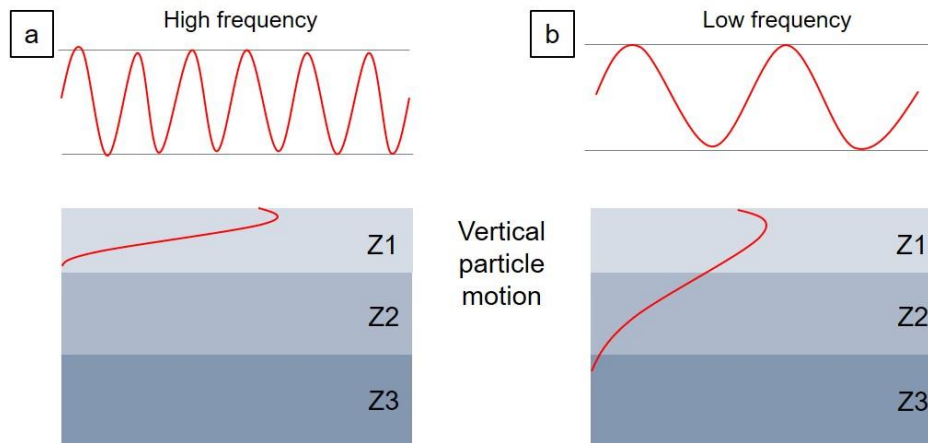


Figure 3.5 (a) High-frequency Rayleigh waves and (b) Low frequency of Rayleigh waves. Rayleigh waves with low frequency (long-wavelength) penetrate deeper than Rayleigh waves with higher frequency (shorter wavelength) [adapted from Foti et al., 2015].

When a seismic record is displayed as a plot of frequency-phase velocity, the Rayleigh waves appear in the form of a curve, known as dispersion curve (DC), defined by the dispersion characteristic of the Rayleigh waves (Fig. 3.6). The multiple phase velocities included in a given frequency create multi-modal DC. The mode with the lowest V_{ph} at each frequency is called the fundamental mode (M0) and exists at all frequencies (Fig. 3.6a). In Fig. 3.6b, is an illustration of higher modes, called 1st higher-mode (M1), a 2nd higher-mode (M2), etc., which have higher phase velocities and exist only above the mode dependent cut-off frequency [Evrett, 2013; Foti et al., 2018].

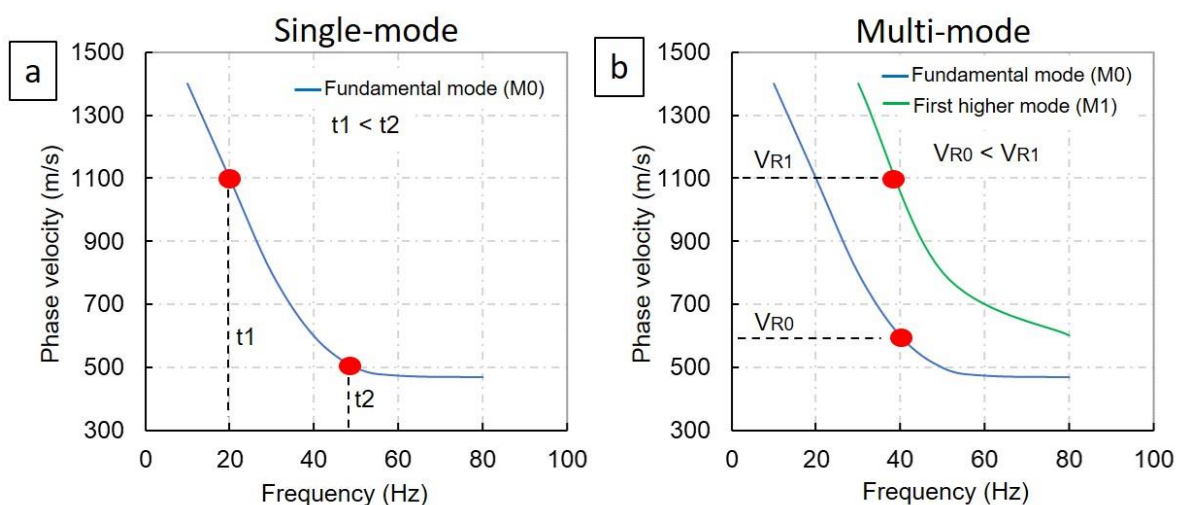


Figure 3.6 (a) The illustration of fundamental mode dispersion curves and (b) The first higher mode dispersion curves [adapted from Foti et al., 2018].

The velocity of the body waves in the geomaterial is directly related to the modulus of elasticity of the medium through which the wave travels. The stress-strain curve (τ - γ) in Fig. 3.7 shows that the shear modulus of soil (G) is highly dependent on strain level. The shear wave velocity (V_s) is a leading indicator of stress-strain behavior in geomaterials (e.g. subsoil site, shallow sediment) due to their relationship to the shear-strain modulus (G_{max}) [Kaldal, 2007; Luna & Jadi, 2000; Wair, DeJong & Shantz, 2012; Ólafsdóttir, 2014]. The soil behavior is nearly elastic for small shear deformations, which means that the shear modulus for small strains can be assumed to be constant at its maximum value (G_{max}).

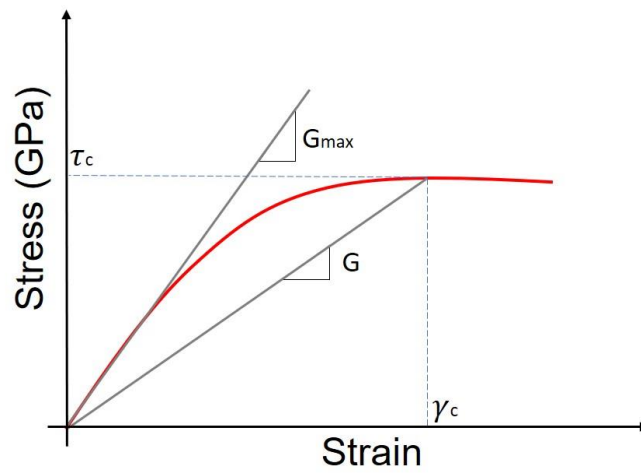


Figure 3.7 Illustration of the stress-strain curve with a variation of shear modulus [adapted from Ólafsdóttir, 2014].

S-wave velocity can be calculated and used to infer the stiffness of the material through which the waves propagate via the shear modulus (G , sometimes referred in literature as μ):

$$G = \rho V_s^2 \quad (\text{Eq. 3.2})$$

where ρ is the mass density of the materials. The maximum modulus elasticity of the soil layers (E_{max}) can be estimated using the relationships between the elastic modulus (E), the shear modulus (G), and the Poisson's Ratio (U) of homogeneous isotropic linearly elastic materials [Evrett, 2013]:

$$E_{max} = 2G_{max}(1+U) = 2\rho V_s^2(1+U) \quad (\text{Eq. 3.3})$$

By using Eq. 3.2 and Eq. 3.3, V_s can be estimated as:

$$V_s = \sqrt{\frac{G_{max}}{\rho}} = \sqrt{\frac{E_{max}}{2\rho(1+u)}} \quad (\text{Eq. 3.4})$$

The Rayleigh wave velocity (V_R) is always lower than the V_s . Bergmann [1954] [cited in Vink & Malischew, 2007] approximated the V_R for isotropic elastic solids as:

$$V_R = \frac{0.87 + 1.12u}{1+u} V_s \quad (\text{Eq. 3.5})$$

The Poisson's ratio is typically in the range of $0.25 < U < 0.35$ for sandy or gravelly sites [Bessason & Erlingsson, 2011]. Thus, for a sediment material with average $U = 0.33$, the estimated Rayleigh wave velocity is $V_R \approx 0.93V_s$.

b. Love Waves

Love waves are surface waves that have a horizontal motion perpendicular to the direction of wave propagation (Fig. 3.2b). Since particles move horizontally, Love waves are rarely documented in surveys that use only vertical sources-receivers [Park et al., 1998]. Love waves are not present in homogeneous materials, and in heterogeneous media the velocity of Love waves depends only on shear modulus (G) and density (ρ) variations with depth. Love waves are constructed by the interaction of S- waves with the Earth's surface and shallow structures that depend on the period of the wave. Generally, earthquakes produce Love waves in the period of interval thousands to seconds, and each period travels at a different velocity but typically ranging at *ca.* 2000-6000m/s [<http://eqseis.geosc.psu.edu/>].

3.2 Multichannel Analysis of Surface Waves (MASW)

The Multichannel Analysis of Surface Waves (MASW) is a seismic technique that uses the propagation properties of surface waves in the near/shallow surface to determine the distribution of shear wave velocity (V_s) in the subsurface. MASW relies on the Rayleigh wave dispersion principle, which is produced by both potential and kinetic energy in both control and natural seismic sources. Rayleigh waves are created by the interference of P-waves and vertically polarized S-waves. It can be used for 1D V_s -depth profile (in single shot record) or 2D V_s -depth

profile (by pasting together the 1D Vs-depth profiles) that result of the inversion from Rayleigh waves dispersion curve.

Seismologists have extensively used surface waves to characterize deep targets of the Earth's crust and upper mantle [Ewing et al., 1957; Dorman and Ewing, 1962; Bullen 1963; Knopoff 1972]. The Spectral Analysis of Surface Waves (SASW) technique, a first approximation to MASW, was introduced in the early 1980s by Heisey et al. [1982]. In order to determine the shear wave velocity profile of soil layers, the SASW approach used the ground roll (or Rayleigh wave dispersion properties) in a multi-layered medium within a single station [Nazarian and Stokoe 1984; Roesset et al., 1991; Stokoe et al., 1994; Park et al. 1999; Xia et al. 1999]. Geophones detect surface waves that are produced by an impulsive source and processed in the frequency domain the dispersion curve can be obtained. The dispersion curve is then employed (extracted) as a basis for the computation of a shear wave velocity profile as a function of depth [Bessason & Erlingsson, 2011; Park et al., 1999]. Meanwhile, the development of multi-station acquisition techniques (multichannel seismic arrays) provided more information on the physical properties of the subsurface. Several authors led to the advancement of acquisition (field measurement), processing (dispersion analysis), and inversion techniques, as well as in a variety of applications [McMechan and Yedlin, 1981; Gabriels et al., 1987; Tokimatsu et al., 1991; Tokimatsu 1995; Lai et al., 1998; Park et al., 1999; Xia et al., 1999; Foti et al., 2000; 2002; Rix et al., 2001].

The surface wave research has progressed since its inception in the early 1950s [Van de Pol 1951; Jones 1955] and has been tested using both the single-receiver technique [Abbiss, 1981; Tokimatsu et al., 1991; Matthews et al., 1996] and the multi-receiver technique [Heisey et al., 1982]. At the end of the 1990s, Park et al. [1999] and Xia et al. [1999] introduced the MASW method, which marked the state of the art in subsequent surface wave studies. Surface waves are generated in the field and documented by multiple receivers (usually 24 channels or more), leading to more efficient data acquisition as well as faster and easier automated data processing. The noise sources recorded, such as body waves and reflected/scattered waves, can be filtered out more easily

and resulting in a more accurate V_S -depth profile than other surface wave methods [Socco et al., 2010; Olafsdóttir, 2014; Foti et al., 2018].

The MASW method aims to reconstruct the V_S -depth profile by solving an inverse problem of input parameters determination with an experimental DC. Typical analysis procedures consist of three sequential steps (Fig. 3.8): (a) acquisition of seismic data (field measurements); (b) data processing (developing DC); and (c) inversion (model parameter optimization) [Socco et al., 2010; Foti et al., 2018]. The following subsections present a summary of these steps to generate 1D and 2D V_S -depth profiles.

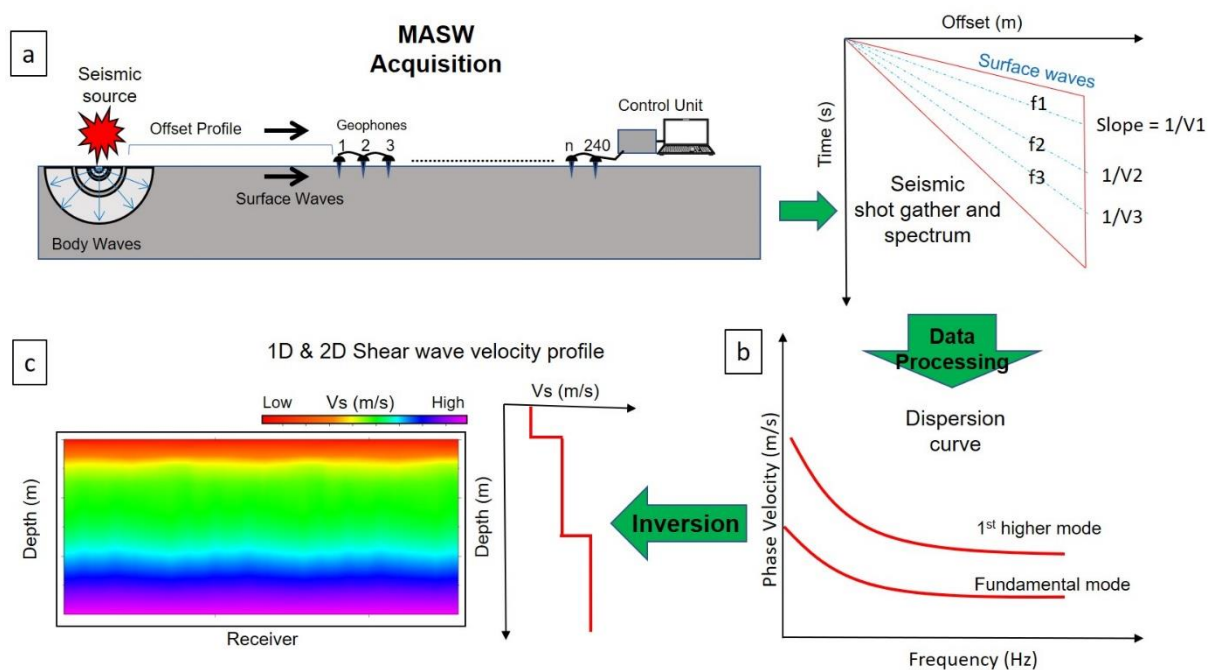


Figure 3.8 Illustration of the MASW procedure. The MASW method involves three stages: a) seismic acquisition, b) data processing, and c) inversion [adapted from <http://masw.com/WhatisMASW>].

3.2.1 Field Measurements (Data Acquisition)

The first step to generate a V_S -depth profile is the collection (acquisition) of data in the study area. Surface waves can be collected using control or natural sources. In the former, surface waves are generated by controlled seismic sources such as sledgehammer, vibrator trucks or explosions. Natural source surveys collect surface waves using natural sources of acoustic noise such as traffic noise, train, animal and/or electrical noise from equipment like refrigerators, air

conditioning units, power supplies, pumps [Park et al., 2007]. Typically, a set of geophones are used, each connected to a separate recording channel [e.g. Park & Carnevale, 2010; Martínez-Pagán et al., 2018].

An example deployment and acquisition geometry of control source seismic data survey is shown in Fig. 3.9. The depth of penetration is influenced by different issues [Park & Carnevale, 2010; Foti et al., 2018]: i) the natural frequency of the observed seismic signal; ii) the array setup, the acquisition geometry used for collecting the data; iii) the instruments sensitivity reflected by the frequency-bandwidth; and iv) the natural velocity of the sediments/rocks in the site. The longest surface wave wavelength (λ_{max}) obtained during data acquisition determines the maximum investigation depth. Then, the receiver spacing (dx) is related to the shortest wavelength that can be analyzed (λ_{min}). The shallowest depth of investigation (Z_{min}) is resolvable between $\frac{\lambda_{min}}{3} < Z_{min} < \frac{\lambda_{min}}{2}$, where $\lambda_{min} \sim 2dx$, being dx the receiver spacing. Meanwhile, the maximum wavelength λ_{max} corresponds to the array length (L), where the value is about $\lambda_{max} \approx L$ [Park & Carnevale, 2010]. Park & Carnevale, [2010] suggested that the maximum penetration depth (Z_{max}) is around $Z_{max} \approx 0.5L$. The expected maximum depth of examination is about from $\frac{\lambda_{max}}{3} < Z_{max} < \frac{\lambda_{max}}{2}$ [Foti et al. 2018].

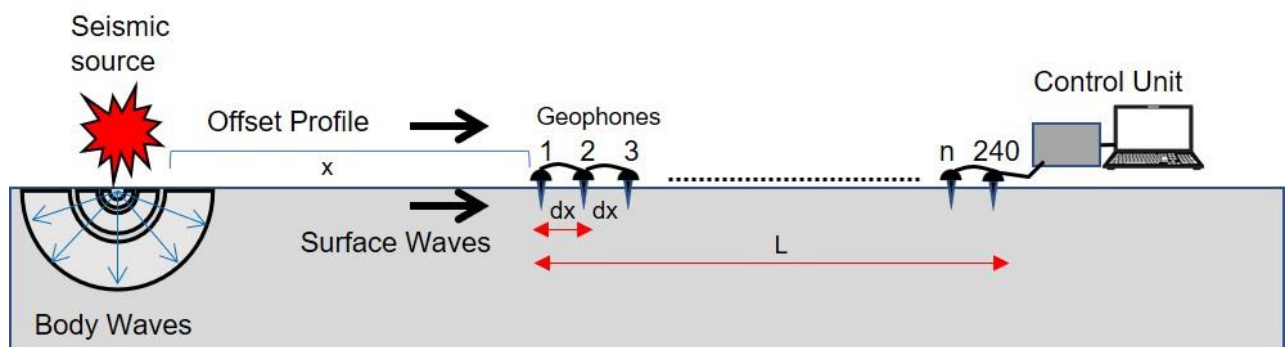


Figure 3.9 Illustration of the seismic data acquisition indicated the geophone spacing (dx) and the source offset (x).

3.2.2 Data Processing

The second step of the MASW procedure is the processing of the seismic data. This stage can be divided in three parts: (i) pre-processing; (ii) processing (developing dispersion curve); and (iii) extracting of dispersion curve. In this section, we also explain the basic theory of the dispersion curve (DC).

a. Pre-processing

The pre-processing step is the initial step that needs to be completed in order to achieve the best surface wave resolution. To improve the S/N ratio, simple and conventional seismic processing can be applied just before estimating the surface wave dispersion diagram. This can include: a trace balancing so that the background noise is consistent for trace to trace; a band pass filter, a spectral balancing, in order to bust the frequency content of the surface wave, spherical divergence to compensate for depth attenuation, among other processing modules. This simple and basic processing aims to increase the lateral continuity and extent of the different phases and increased the energy of the S-wave arrivals. The seismic data presented here features a high amplitude of dispersive surface waves, which is very prominent in the shot records (Fig. 3.10).

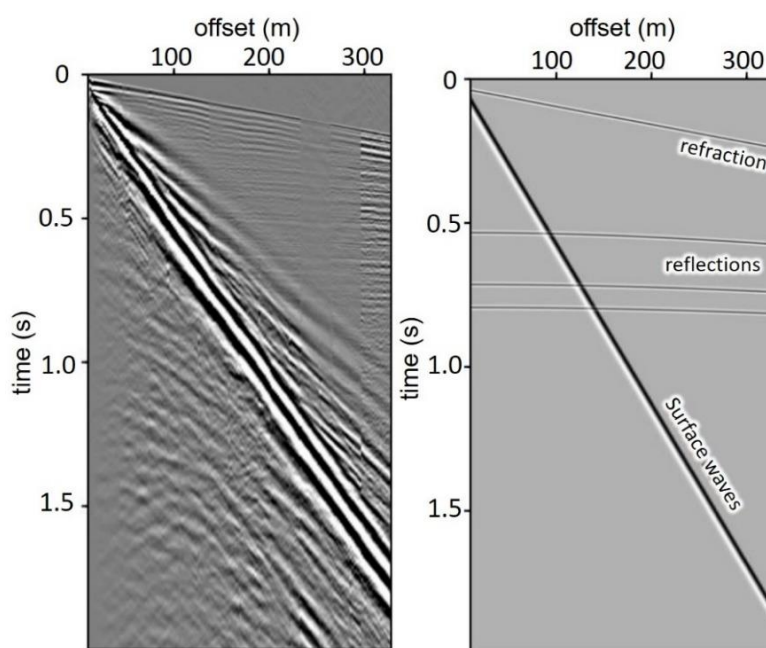


Figure 3.10 This corresponds to a shot gather and illustrates the different seismic events: refractions, reflections, and high amplitude surface waves in seismic shots gather [adapted from <https://webthesis.biblio.polito.it/15687/1/tesi.pdf>].

b. Processing (developing dispersion curve)

The estimation of the dispersion diagram is the key step of the MASW analysis. This step aims to develop a DC the bibliography concerning this point is very broad and extensive [see for example Park et al., 1999; Foti et al., 2018 and references therein]. The dispersion diagram reveals the surface wave field in terms of frequency and phase velocity ($V_{ph}-f$) or phase velocity-wave number ($V_{ph}-k$) behavior of surface waves at a survey area. This information is critical as the penetration depth of surface waves is a function of its wavelength (note that this has been introduced in the previous sections). Several methods have been developed for extracting DC from recorded multichannel data. The data recorded in the field, that is in the time offset space ($t-x$) domain, need to be converted into either the frequency-phase velocity ($f-V_{ph}$) or the frequency-wavenumber ($f-k$) domain [McMechan & Yedlin, 1981; Park et al., 1998; Foti et al., 2018; among others]. In this memoir, we followed two slightly different approaches to obtain the dispersion diagrams. In one the ($t-x$) shot records were transformed to intercept time-ray parameter domain. This is ($\tau-p$) transform, then a frequency-spectra of the ($\tau-p$) transformed record was computed [Park et al., 1998]. This processing flow was carried out using Seismic-Unix standard modules, and compared to the output of the “*suphasevel*” module which produces the Phase-velocity dispersion map directly from the shot record. The advantages of the former processing flow is that it allows for noise attenuation when shot gathers are noisy, and in this way the dispersion curves become qualitatively clearer.

Nevertheless, in most cases the application of the standard Seismic-Unix “*suphasevel*” module [Cohen and Stockwell, 2010] was sufficient to be able to identify the dispersion characteristics of the surface waves. This, the phase velocity spectrum was then used to extract one or more dispersion curves “DC” (multi-mode: fundamental mode and higher mode) due to the energy content of the recorded surface wavefield [Xia et al., 2002]. The example of DC is shown in Fig. 3.11a.

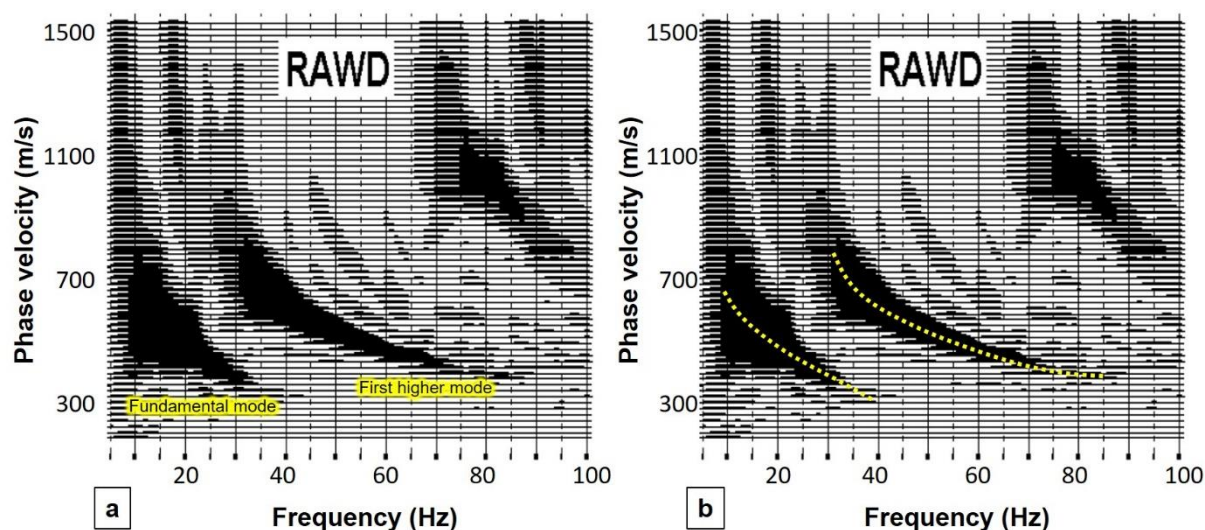


Figure 3.11. a) The example of DC with the fundamental mode and first higher mode diagrams; and b) The example of extraction DC. The yellow dots line is the example of the extracted dispersion curve from the best fit of highest amplitude [modified from Park et al., 2002].

High-resolution dispersion images are essential for extracting fundamental and/or higher mode DC to proceed to the inversion analysis. The sharpness of an image is controlled by its resolution, which is defined by the number of pixels contained in a unit area, quantifying the nearness of the pixels until the limit of being visibly resolved.

Park et al. [1998] described dispersion curve (DC) image resolution as two resolvable independent terms, namely resolution along the phase-velocity axis and resolution along the frequency axis. For a given frequency, the resolution along the velocity axis represents the ability to distinguish between the particular phase velocities with the highest local energy and the other adjacent phase velocities with lower energies. In contrast, the resolution along the frequency axis can be described in terms of a given phase velocity [Park et al., 1998; Zhang et al., 2004].

The generation of high-resolution DC images is resolved by several parameters, the significant proportion of which are related to data acquisition (offset, receiver spacing, source energy) and data characteristics (sampling frequency). Furthermore, stacking dispersion images (combining dispersion images obtained from repeated test analysis) enhances the energy content of different frequencies, leading to a high-resolution DC image.

c. Extracting the dispersion curve

From the dispersion diagram a dispersion curve was then digitized (dispersion curve extraction) to obtain a velocity and frequency series. In this memoir it is assumed that the fundamental mode corresponds to the dominant mode revealed by the wavefield, only this mode was considered. The picking process of the fundamental mode ($V_{ph}-f$) was supervised by the operator. Figure 3.11b shows the picked fundamental mode of measured data as a yellow dot line. The fundamental mode describes in a simplified form the dispersion characteristics of the wavefield and it can be inverted to obtain a velocity-depth profile [Park et al., 1999; Xia et al., 2002].

Theoretical dispersion curve

Matrix methods based on wave propagation theory are commonly used to determine theoretical dispersion curves. Thomson [1950] developed and presented the forward model and dispersion due to a seismic wave propagating through on stratified media. To calculate surface wave dispersion curves for a horizontally layered media the Thompson-Haskell approach can be used [Haskel, 1953], it is broadly known as the transfer matrix method. It constitutes the base of several approaches for examining surface wave propagation in layered media [see for example Schwab and Knopoff 1970; Knopoff, 1972; Kausel and Roësset 1981].

The dispersion data of Rayleigh waves in a layered media can be described as a function F of five parameters: V_P , V_S , mass-density, and layer thickness:

$$F(f_j, V_{phj}, V_P, V_S, \rho, h) = 0 \quad (j = 0, 1, 2, \dots, m) \quad (\text{Eq. 3.6})$$

where f_j is the frequency (propagating wave). The S- wave velocity vector is $V_S = (V_{S1}, V_{S2}, V_{S3}, \dots, V_{Sn})^T$, with V_{Si} corresponds to the V_S of the i^{th} layer. The P- wave velocity vector is $V_P = (V_{P1}, V_{P2}, V_{P3}, \dots, V_{Pn})^T$, with V_{Pi} the V_P of the i^{th} layer. The density vector is $\rho = (\rho_1, \rho_2, \rho_3, \dots, \rho_n)^T$, with ρ_i the density of the i^{th} layer and $h = (h_1, h_2, h_3, \dots, h_{n-1})^T$ corresponds to the thickness, with h_i the thickness of the i^{th} layer (Fig. 3.12).

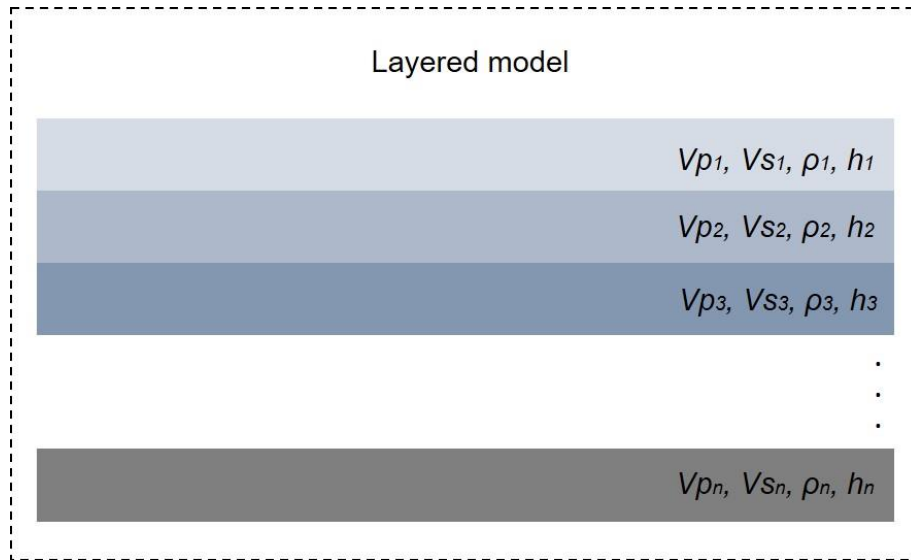


Figure 3.12 The example of initial model to develop the theoretical dispersion curve and inversion process.

Rayleigh-wave phase velocity (dispersion data) is dependent on the four parameters: S-wave velocity, P-wave velocity, density, and layer thickness [equation (3.6)]. Each parameter contributes to the dispersion curve in a unique way. A parameter can be negated from the inverse procedure if contributions to the dispersion curve from that parameter are relatively small in a certain frequency range [Xia et al., 1999]. Equation 3.6 is a nonlinear relationship between the different parameters.

3.2.3 Solution of the Inversion Problem

The solution of the inverse problem is a relevant point in the research that has been carried out. In general, the inversion strategy involves minimizing the misfit between on-site observations and synthetic simulations. Classical reference material to the solution of inverse problems include: Tarantola and Vallete 1982; Menke, 1984; Snieder and Trampert, 1999 among many other authors]. This section is of special relevance to the research carried out thus a short review will be given as different aspects and processes of this development are refereed to within this memoir.

For the formulation of the inverse problem, we take into account the measured observables indicated by d_i . For example, if the target is the Vs velocity model, d_i correspond to the digitized

dispersion curved extracted from the dispersion observations (the dispersion diagram), and more specifically the dispersion curve in terms of frequency phase velocity. In the case were P- wave velocity models are to be determined d_i correspond to the travel time of the first arrivals.

In both cases, a simple approximation to the subsurface media is considered particularly a 2D layered model such as in Fig. 3.12. In both cases, the relationship between the model parameters m_j are related to the observation by some sort of nonlinear functional relationship such as equation 3.6. Taking into account the notation reflecting data and model parameters in both cases (Equation. 3.6) will be:

$$F(d_i, m_j) = 0 \quad (\text{Eq. 3.7})$$

Ideally, in many instances, Eq. 3.7 can be expressed as:

$$d - G(m_j) = 0 \quad (\text{Eq. 3.8})$$

G is a nonlinear function that solves the forward model. The difference expresses in Eq. 3.8 is usually not zero as measurements are usually affected by errors and the theoretical calculations are based on relatively simple parametrizations of the model, (Fig. 3.11 in our case). For example, in the case of the V_p inversion G would correspond to ray tracing solution of the wave equation. This functional relationship is nonlinear. The inverse problem aims to minimize the difference between the observed, measurements and the theoretical estimates considering the chosen parameterization:

$$d^{\text{obs}} - d^{\text{theoretical}} = d^{\text{obs}} - G(m^{\text{est}}) = e \quad (\text{Eq. 3.9})$$

The value of e stands for error estimates. The ideal solution of Equation 3.9, will correspond to the values of the model parameters m_j that minimize 3.9. As there are usually a large number of observables, in other words, “ e ” (Eq. 3.9) is a vector, thus the magnitude (length of the vector) needs to be minimized. This is carried out by using a norm (L_1 L_2 , ... L_n) has to be chosen:

$$\begin{aligned} L_1 \text{ norm } \|e\|_1 &= [\sum \|e\|^1] = (d - Gm) \\ L_2 \text{ norm } \|e\|_2 &= [\sum \|e\|^2] = (d - Gm)^T (d - Gm) \\ L_n \text{ norm } \|e\|_n &= [\sum \|e\|^n] = \dots\dots\dots \end{aligned} \quad (\text{Eq. 3.10})$$

In most cases the Euclidean L_2 norm is used. At this point is convenient to remember that the functiona G is nonlinear. Minimizing L_2 and iterative scheme is reached. Developing the minimization of L_2 and considering that the problem is under-determined (this implies that the number of data observations < that the number of parameters or unknowns). The final iterative algorithm, also known as the weighted damped least squares solution is [Tarantola and Vallete 1982; Menke, 1984]:

$$\mathbf{m}^{\text{est}} = \langle \mathbf{m} \rangle + \mathbf{W}_m^{-1} \mathbf{G}^T [\mathbf{G} \mathbf{W}_m^{-1} \mathbf{G}^T + \mathbf{W}_d^{-1}]^{-1} [\mathbf{d} - \mathbf{G} \langle \mathbf{m} \rangle] \quad (\text{Eq. 3.11})$$

$\langle \mathbf{m} \rangle$ is the array of estimated parameters in the previous iteration of algorithm. Therefore, a $\mathbf{m}_0$ or starting model is required to apply this scheme. This starting model is assumed to be close to the true solution. Furthermore, in Eq. 3.11, $\mathbf{W}_m$ and $\mathbf{W}_d$ correspond to the covariance matrix or estimated error distribution for the parameters and the data observables respectively. $\mathbf{G}$ is the Jacobian matrix of the functional relationship (Equation 3.11). $\mathbf{G}^T$ is its transpose. A priori information can be included in the algorithm for example we can look for simplest model solution by establishing:

$$L = \|\mathbf{m}_i - \mathbf{m}_{i-1}\|^2 = \xi(\mathbf{m}_i - \mathbf{m}_{i-1})^2 = \text{Roughness function} \quad (\text{Eq. 3.12})$$

This condition establishes that the model parameters should be smooth. A smooth model condition is the key in the Occam's inversion algorithm.

a. Inversion utilities for the shear wave velocity-depth profiles

A modified version of SWAMI [Glenn & Lai, 2002; Pelekis and Athanasopoulos 2011] software has been used integrated within Seismic-Unix modules. SWAMI (Surface Wave Analysis, Modeling, and Inversion) solves the nonlinear inverse problem of estimating the shear wave velocity profile given a surface wave dispersion curve (i.e., phase velocity vs. frequency) and associated uncertainties, which are assumed to represent the fundamental mode of propagation. The medium is assumed to be elastic and the solution of the inverse problem is

uncoupled from the related problem of estimating the shear damping ratio profile from surface wave attenuation data.

The inversion algorithm is based on Constable, et al., [1987]. The strategy of the algorithm is as follows: given an experimental dispersion curve and associated uncertainties, find the smoothest shear wave velocity profile subject to the constraint of a specified misfit between experimental and theoretical data. As the algorithm search for the smoothest velocity depth profile, the roughness criteria (Equation 3.12) is incorporated in the generalized inversion scheme (Equation 3.11) Convergence is defined as achieving a root-mean-square (RMS) error of 1.0 or less (i.e., the specified misfit) or a negligible change in the shear wave velocity profile from one iteration to the next. A maximum of 10 iterations is allowed. The user may change these parameters as desired. For a detailed description of the inversion algorithm, see Lai and Rix [1998].

The forward algorithm used to calculate theoretical dispersion curves and partial derivatives of the phase velocity with respect to the shear wave velocity of each layer is based on Hisada, Y., [1994]. Lai, C.G., [1998]. An estimate of the uncertainty of the final shear wave velocity profile is calculated based on Lai, et al., [2005].

b. Hands on Inversion utilities for the P wave velocity-depth profiles

The P-wave velocity characterization of the shallow subsurface was addressed by using a couple of different approaches which correspond to available software packages, furthermore we also employed available utilities from commercial packages such as Globe Claritas to help and asses the travel time picking phase of the processing. As the array of data points used for the travel time inversion (d_j in Equation 3.11) correspond to the first arrival travel time of the seismic energy in the shot records. With Claritas' travel time picking utility over 90% of the data picks were automatically digitized due to the relatively high signal-to-noise ratio of the seismic records, which include all the offset ranges, reaching to maximum offsets of approximately 500 m. This offset range assures a good resolution down to 150 m. For the inversion part of the tomography two different approaches where considered.

Least square seismic inversion of first arrival travel times

A broadly known academic 3D tomographic code Pstomo_eq [Benz et al., 1996; Tryggvason et al., 2002] was used to perform the travel time inversion. This code solved the inverse problem through Equation 3.11, least square approach (L_2 norm). The forward modeling part (G_m in Equation 3.10) of the algorithm, performs the travel time computations. These computations are carried out by solving the Eikonal equation [Podwin and LeComte 1991]. Once the travel-times from shot point to receiver point are calculated, the ray paths are determined by tracing them perpendicular to the isochrons map [Vidale., 1988]. Further specific details on this software utility can be found in: Hole and Zelt [1995]; Tryggvason and Bergman, [2006]; Tryggvason et al., [1996] and reference therein.

Seismic refraction inversion of first arrival travel times

For shallow subsurface a number of available refraction tomography codes are available. A broadly used one is the 1D Delta-T-v. This code is an alternative approach to the interpretation of seismic first breaks, as first described by Gebrande et al., [1985], Gebrande [1986]. This methodology assumes that subsurface velocity varies smoothly in the vertical direction. It mostly works in the Common Mid Point (CMP) space, therefore, travel-times need to be sorted into CMP instead of shot gathers. This sorting process averages out the effects of dipping layers on the travel-times.

The travel-times are smoothed by stacking the CMP-sorted travel-time curves over a few adjacent CMP's. After this averaging process each CMP curve is independently inverted by the software program and a 1D velocity depth function is obtained. The velocity depth function is based on "seismic stripping scheme". This scheme involves assuming incremental layers featuring constant vertical velocity gradients and positive or negative velocity steps at layer boundaries. The constant velocity gradient assumption simplifies the forward modelling, as rays being traced follow circular arc segments inside each layer. As a consequence, rays can be reconstructed and treated analytically.

The method estimates the layer bottom velocity from travel-times and then inverts for the layer top velocity by solving a system of two equations numerically. This procedure does not involve the details presented and discussed in section above related to the resolution of inversion problems (Equation 3.11). Seismic stripping is equivalent to physically placing the source and receivers each stripping step at the top of the layer bellow. Inversion of these reduced travel-times and offsets constraints the properties of the lower layer. Sources are considered in all the process as point sources. The code is able to model diffraction of seismic rays at the top of an inferred low velocity layer. The method automatically detects systematic time delays on CMP curves and translates these delays into velocity inversions. Estimated velocities and layer thicknesses are corrected for inferred velocity inversions. For each CMP location a 1D velocity depth model is determined. Pasting together each velocity depth profile a 2D velocity model can be constrained.

CHAPTER 4
APPLICATION MASW METHOD IN EASTERN
BETIC SHEAR ZONE

“Science without religion is lame, religion without science is blind”.
— Albert Einstein

CHAPTER 4

APPLICATION MASW METHOD IN EASTERN BETIC SHEAR ZONE

The near-surface elastic parameter model is essential for shallow subsurface studies in geophysics, geology, geotechnical engineering, and global geoscience. Surface waves control the seismic wave field near the surface and are of particular concern to scientists due to the considerably high signal-to-noise ratio (SNR). Surface waves have become popular as a non-invasive method of estimating shallow subsurface features over the last two decades, where the analysis of surface waves is becoming a broadly used way to unravel the structure and/or physical properties of the shallow subsurface [e.g. Park et al., 1999; Xia et al., 2002; Ivanov et al., 2006; Boiero and Socco, 2010]. The analysis of surface waves a non-invasive, indirect geophysical characterization method that is widely applied. It has several advantages including: low-cost data acquisition effort; simple and fast data processing and interpretation; a relatively high-resolution (at least for the target depths which are usually below 200 m) [e.g. Park et al., 2016; Xia et al., 2002; Ivanov, 2006; Socco et al., 2010; Duffy et al., 2014; Mi et al 2017; Foti et al., 2018; Catchings et al., 2020; and references therein].

This chapter describes the research that was carried out in the Eastern Betic Sear Zone (EBSZ), one of the most active zones in the Iberian Peninsula. The investigations involved the characterization of the shallow subsurface by means of different methods, however emphasis was placed on MASW. This chapter consists of four sections: i) the first focused on the data, data acquisition across the Alhama de Murcia and Carrascosy Faults; ii) MASW processing: dispersion curves analysis; iii) obtaining V_s , shear wave velocity profiles by inversion of the dispersion curves: 1D and 2D S-wave velocity-depth functions; and iv) P- wave velocity-depth profile building using P- wave tomography.

4.1 Seismic data

In this memoir, a seismic data acquisition survey was conducted in 2017 by the Geociencias Barcelona (GEO3BCN, CSIC) research team as part of the INTERGEO project (Ref: CGL2013-47412-C2-1-P) in the vicinity of the city of Lorca, SE Iberian Peninsula (Fig. 4.1). The surveyed study involves three areas totaling four seismic transects which were named as: La Torrecilla, La Salud North, La Salud South and Carrascoy, the names make references to specific localities and/or areas.

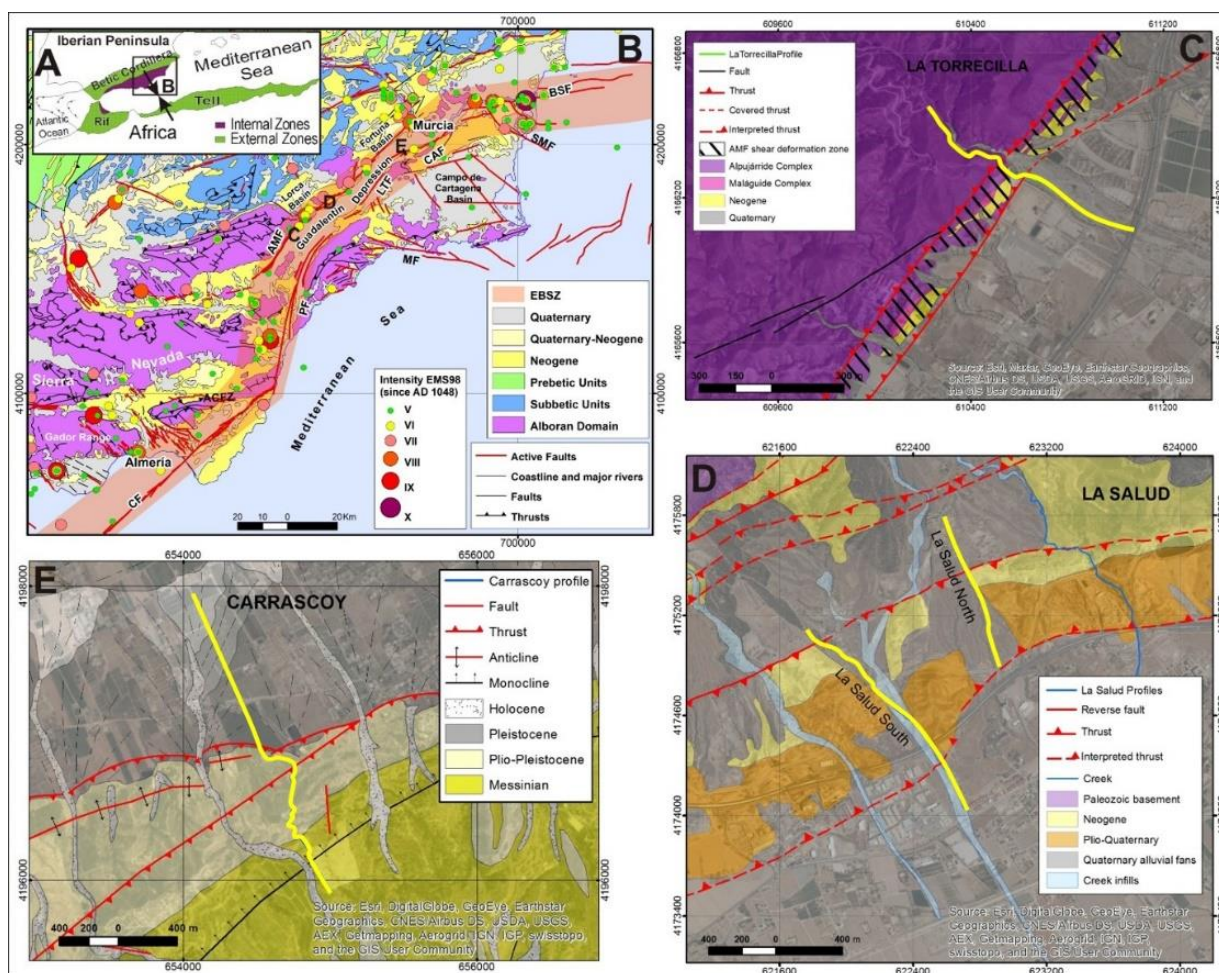


Figure 4.1 Geological map of the study area. Detail maps of the specific transects are also displayed. A) Geodynamic frame of the study area; B) Geological and seismological setting of the EBSZ; C) Geological setting of the La Torrecilla; D) Geological setting of the La Salud North and La Salud South profiles; and E) Geological setting of the Carrascoy profile [modified from García-Mayordomo et al., 2012; IGME, 1998; Marín-Lecgado et al., 2011; IGN-UPM, 2013; Martínez-Díaz et al. 2018; Gómez-Novell, 2021; Martín-Banda et al. 2016].

The seismic data was acquired by a 240-channel system which consisted on ten GEODE recording units connected together. Each GEODE system involved 24 channels. The data were recorded using conventional single component vertical exploration geophones with a natural frequency of 10 Hz. The seismic source used was a 200kg accelerated weight-drop belonging to the Instituto Politécnico de Lisboa (Portugal), also a 60 kg accelerated weight-drop belonging to the University of Oviedo (Spain) was also available as spare part. The data recording sample rate was of 1 ms and the total recording time was 4 seconds. The Spanish National Research Council, CSIC follows the EU open access mandate and therefore, the data can be accessed through the SeisDARE open-access seismic data repository (<https://digital.csic.es/handle/10261/179734>) [DeFelipe et al., 2021].

The acquisition was carried out by leapfrog scheme along the recording spread (cable). Within this scheme, once the source was located at the spread's center, half of the recording spread was moved just before the current source location. Then shooting started again, thus the leapfrog nomenclature. The source was fired every 6 m moving along the spread until the source position reached, approximately half of the spread. The geophone spacing was $dx = 2$ m. A summary of the acquisition parameters of this study is shown in Table. 4.1

Table 4.1 Description of the seismic parameters in the study area.

Seismic survey parameter		Description
Seismic source		Accelerated weight-drop (200 kg)
Source interval		6 m
Transect Lengths	La Torrecilla	1278 m
	La Salud North	960 m
	La Salud South	1488 m
	Carrascoy	2496 m
Receiver interval		2 m
Geophone Natural Frequency		10 Hz
Recording Time		4 s
Sample rate		1 ms

4.2 Processing

4.2.1 Seismic data processing

The first step of seismic data processing is the application of the geometry setup this is taking into account the source and geophone positions for each shot point, this was applied to all acquired transects (Fig. 4.1). The “x”, “y”, and “z” coordinates of each source and receiver position were introduced in the trace headers of the seismic traces. The observer notes were used to incorporate the acquisition geometry (i.e. source and receiver UTM coordinates). This information was used to calculate the offset (i.e. the distance between seismic source and receiver) and azimuth (i.e. the horizontal angle from a cardinal direction, most commonly north) for each trace in all shot records. This information is a conventional part of the SEG-Y [Barry et al., 1975] format seismic trace header.

To achieve the optimum results of seismic surface waves arrivals, high-quality seismic data (with a high S/N ratio) is required. To increase the S/N ratio, a conventional seismic processing workflow was applied to the data, mostly consisting in attenuating the high frequency signal and balancing (normalization) of the amplitudes. In this study, bandpass filters (10-45 Hz) and spherical divergence correction to account for the energy loss were applied (Fig. 4.2b). This basic processing increased the lateral continuity and extent of the different phases and increased the energy of the S-wave arrivals. The shot records particularly show the typical dispersion character of the surface waves featuring very high amplitudes in the area between the red lines (Fig. 4.2b). The frequency content in this region is mostly distributed between 5-60 Hz frequency band (Fig. 4.2c).

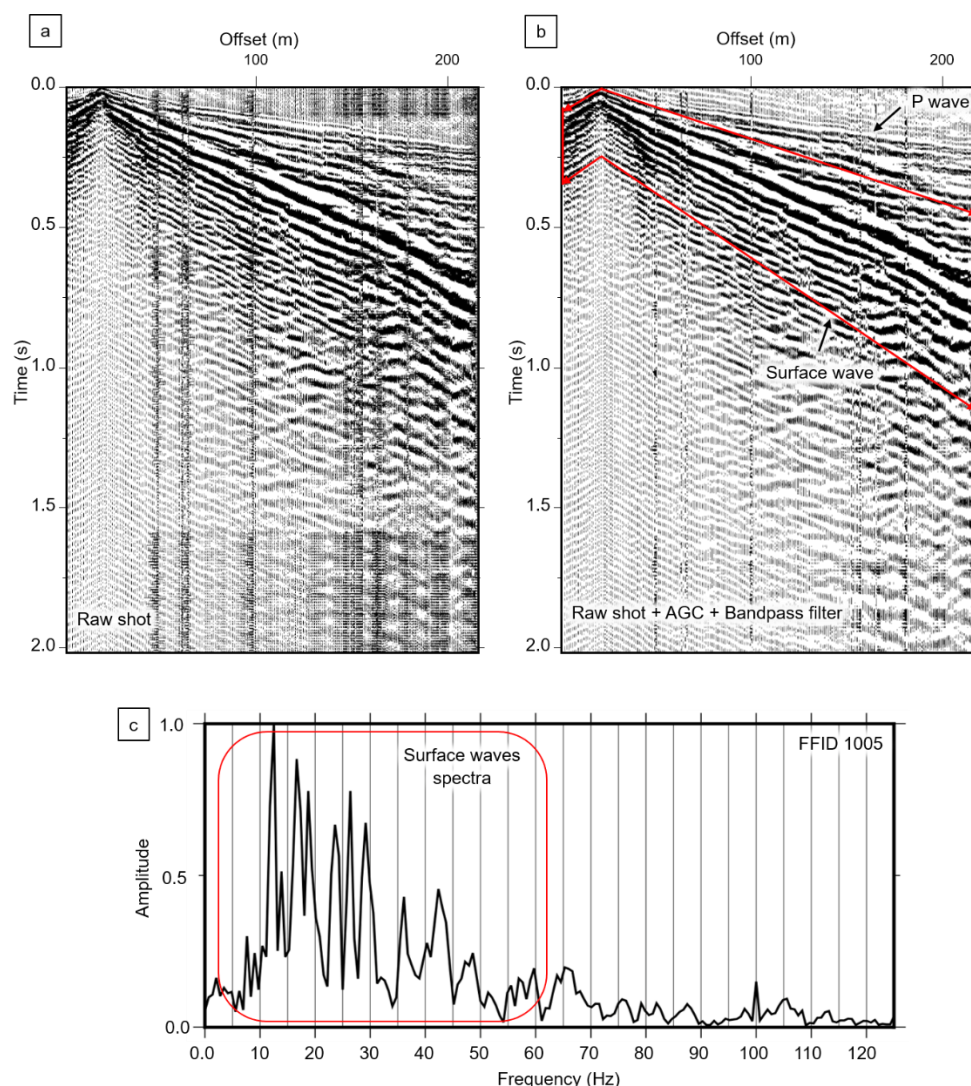


Figure 4.2 The example of shot record FFID 1005 acquired within the Carrascoy profile after different steps data processing: a) The raw shot gather; b) The raw data with a bandpass filter, and amplitude corrections applied. The surface waves are identified by the area between red lines; and c) Frequency spectra of seismic shot gather.

The simple and basic processing sequenced involved: bandpass filter in frequency window 5-45Hz, automatic gain control (AGC), and spherical divergence correction. This seismic processing flow was applied to all the raw shot gathers of the different profiles, examples of shot records of all profiles are shown in Fig. 4.3.

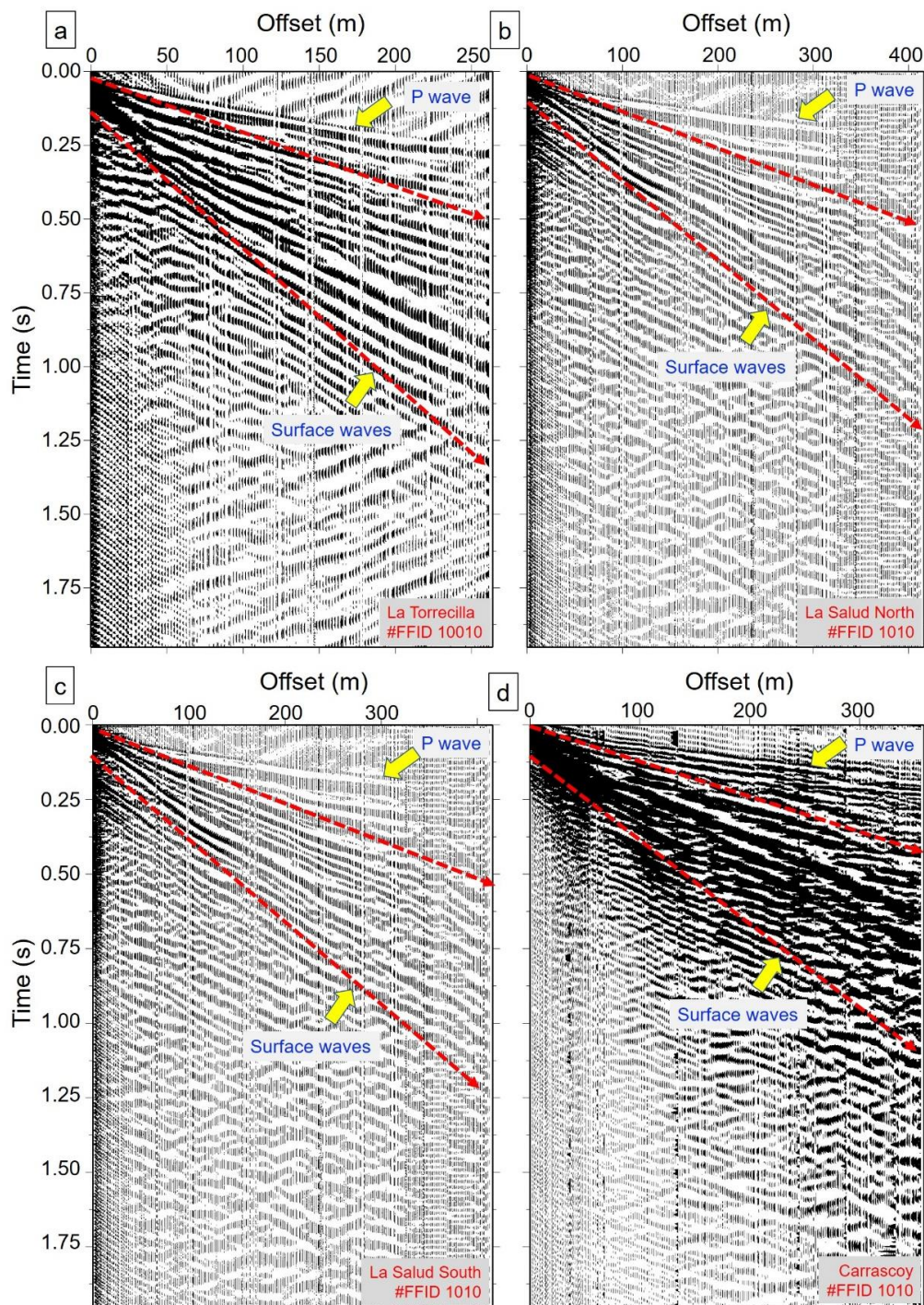


Figure 4.3 The example of short records of the study area with the identified surface waves. a) the Torrecilla profile; b) the La Salud North profile; c) the La Salud South profile; and d) the Carrascoy profile.

4.2.2 Dispersion/Phase velocity diagram analysis

A dispersion/phase velocity curve is a plot of the frequencies and phase velocities of seismic surface waves. The estimation of the dispersion curve from the seismic surface waves is a key step in estimating the Vs-depth profile [Park et al. 1999]. The dispersion curve was obtained by: first perform the Tau-p transform of the shot records, which provides the ray parameter, intercept-time diagram (phase slowness-intercept-time) and, then transform this into the frequency domain obtaining the frequency-phase velocity or dispersion diagram.

The phase velocity spectrum can be used to identify and extract one or more dispersion curves (multi-mode: fundamental mode and higher modes) depending on the energy content of the recorded surface wave-field [Xia et al., 2002]. The fundamental mode is the phase velocity with the lowest frequency, and all phase velocities higher than the fundamental mode velocities are referred to as higher modes [Xia et al., 2002]. The observed high-amplitude band shows the characteristics of the surface wave dispersion. The results of dispersion curve of this study are shown Fig. 4.4: La Torrecilla profile, Fig. 4.5: La Salud North profile, Fig. 4.6: La Salud South profile, and Fig. 4.7: Carrascoy profile.

In Fig. 4.4 (La Torrecilla profile), high amplitudes occur in the frequency range from 5-60 Hz and phase velocities of 200-1300 m/s. In shot number (hereby “FFID”¹) 10010, the dispersion curve diagram shows a clear image of multi-mode surface waves, namely the fundamental mode (M0) and the first higher mode (M1) (indicated by the yellow arrows in Fig. 4.3 to 4.6). In the top left corner of Fig. 4.4 (FFID 10125), the trend of the maximum energy (amplitude) of the surface waves follows the direction of the fundamental mode from about 10-40 Hz. The trend of the first higher mode is clearly visible in the 15-25 Hz interval frequency. The multi-mode of surface waves is also quite clearly visible on id shots FFID 10100-10180 and less visible on id shots FFID 10200-102130.

¹“FFID” stands for *Field File Identification Numbers*, or the unique number for each shot point in SEG Y format, it is also cold field record number (Seismix-Unix).

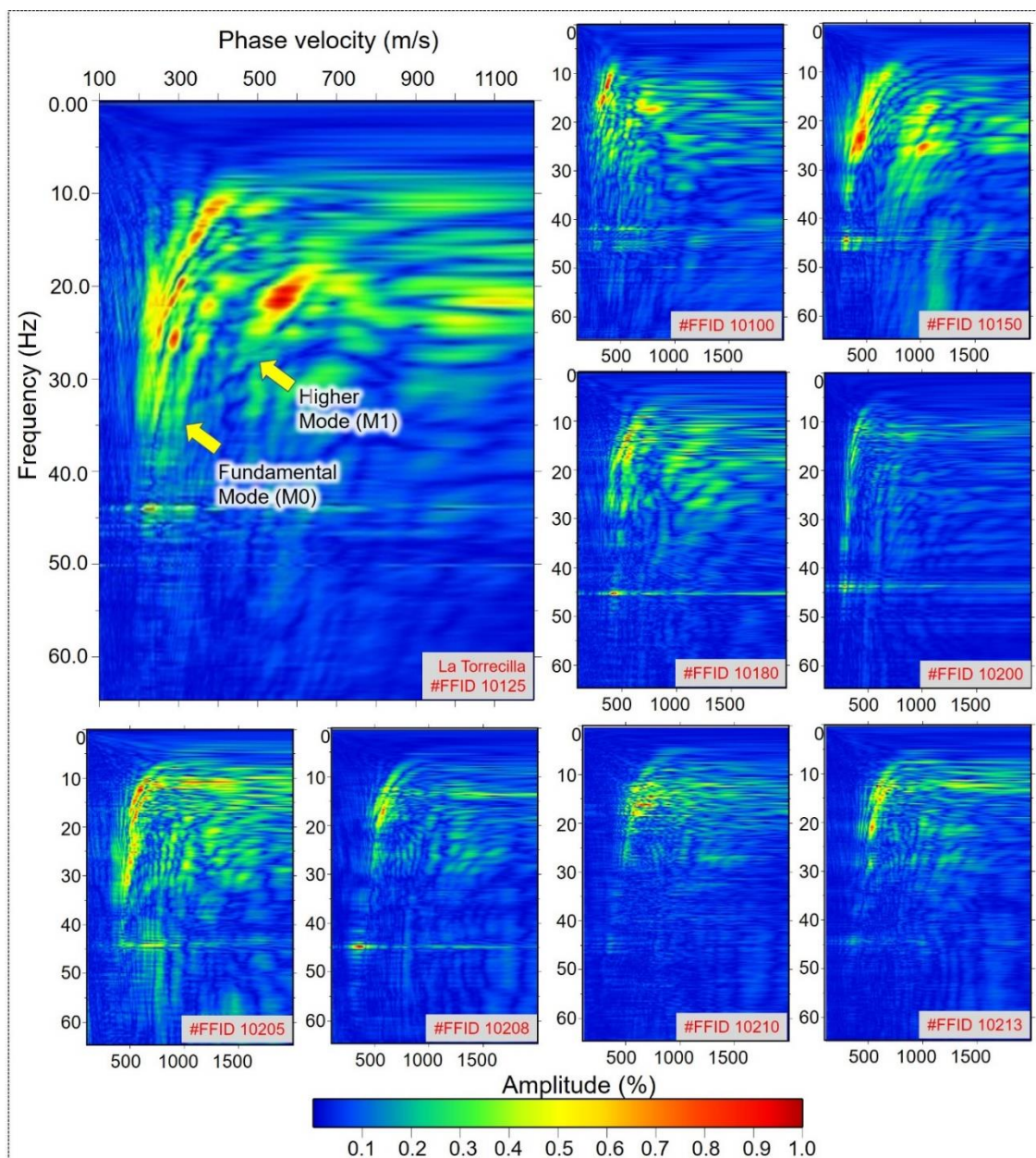


Figure 4.4 The example of DC of the La Torrecilla profile.

Fig. 4.5 shows different dispersion diagrams of a number of shot records from La Salud North profile. The high amplitudes occur in the frequency range of 5-60 Hz and the phase velocities of 200-1300m/s. In FFID 1010, the trend with maximum energy (amplitude) clearly follows the direction of the fundamental mode from about 10-60 Hz. The trend of the first higher mode is clearly visible in the frequency of 15-40 Hz. The multi-mode of surface waves can also be identified on shots FFID 1010-1100. However, the multi-mode of surface waves is less visible on shots FFID 1125-1162.

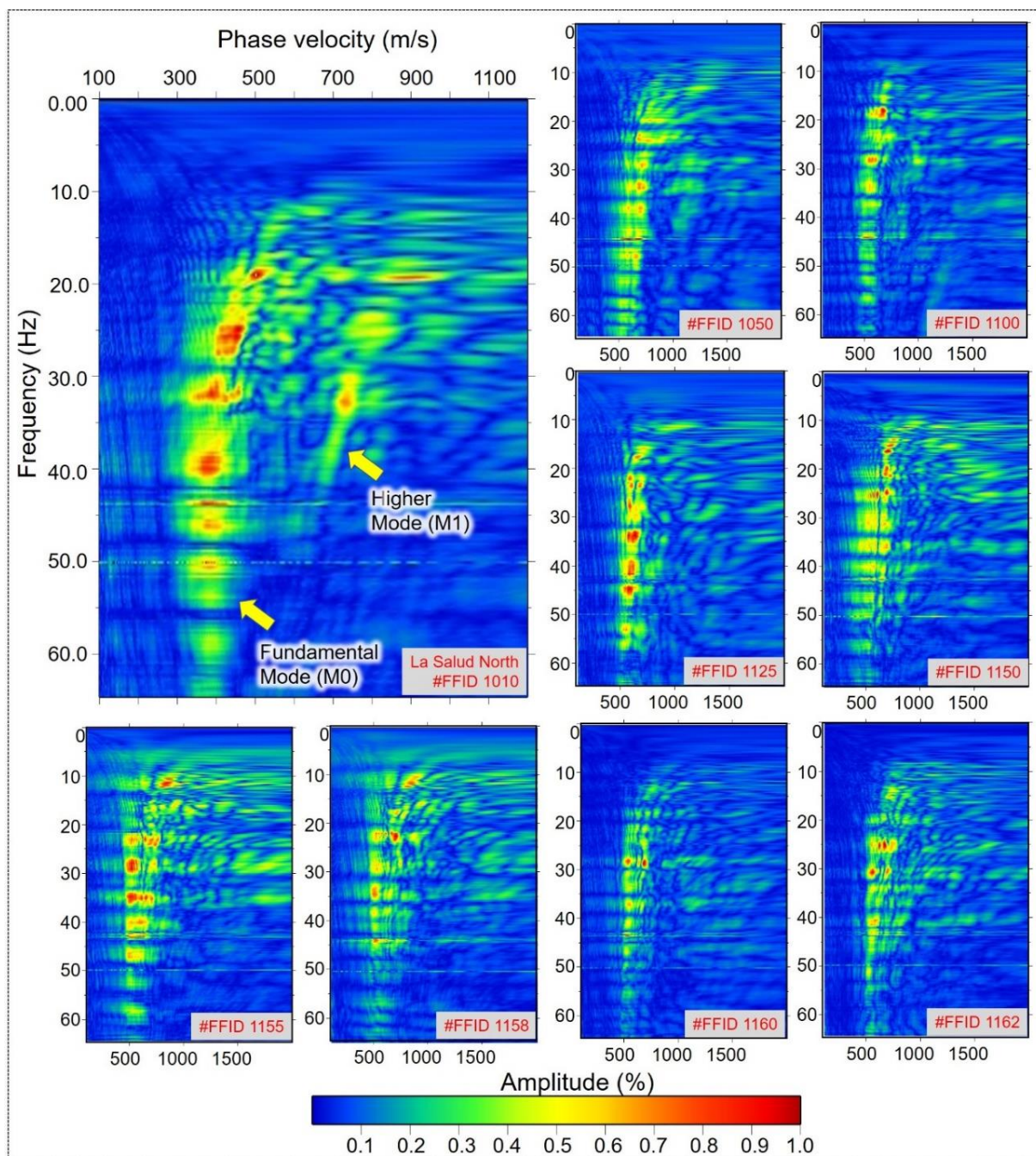


Figure 4.5 The example of DC of the La Salud North profile.

Fig. 4.6 is the example of the dispersion curve at the La Salud South profile. The high amplitudes occur in frequency interval 5-60 Hz and phase velocity 200-1300 m/s. In FFID 1010, the trend with maximum energy (amplitude) clearly follows the direction of the fundamental mode from about 10-40 Hz. The trend of the first higher mode is clearly visible in the 15-25 Hz interval frequency. The multi-mode of surface waves is also quite clearly visible on FFID 1010-1175 and

FFID 1200-1249. However, the multi-mode of surface waves is less visible in middle shots (FFID 1100-1150).

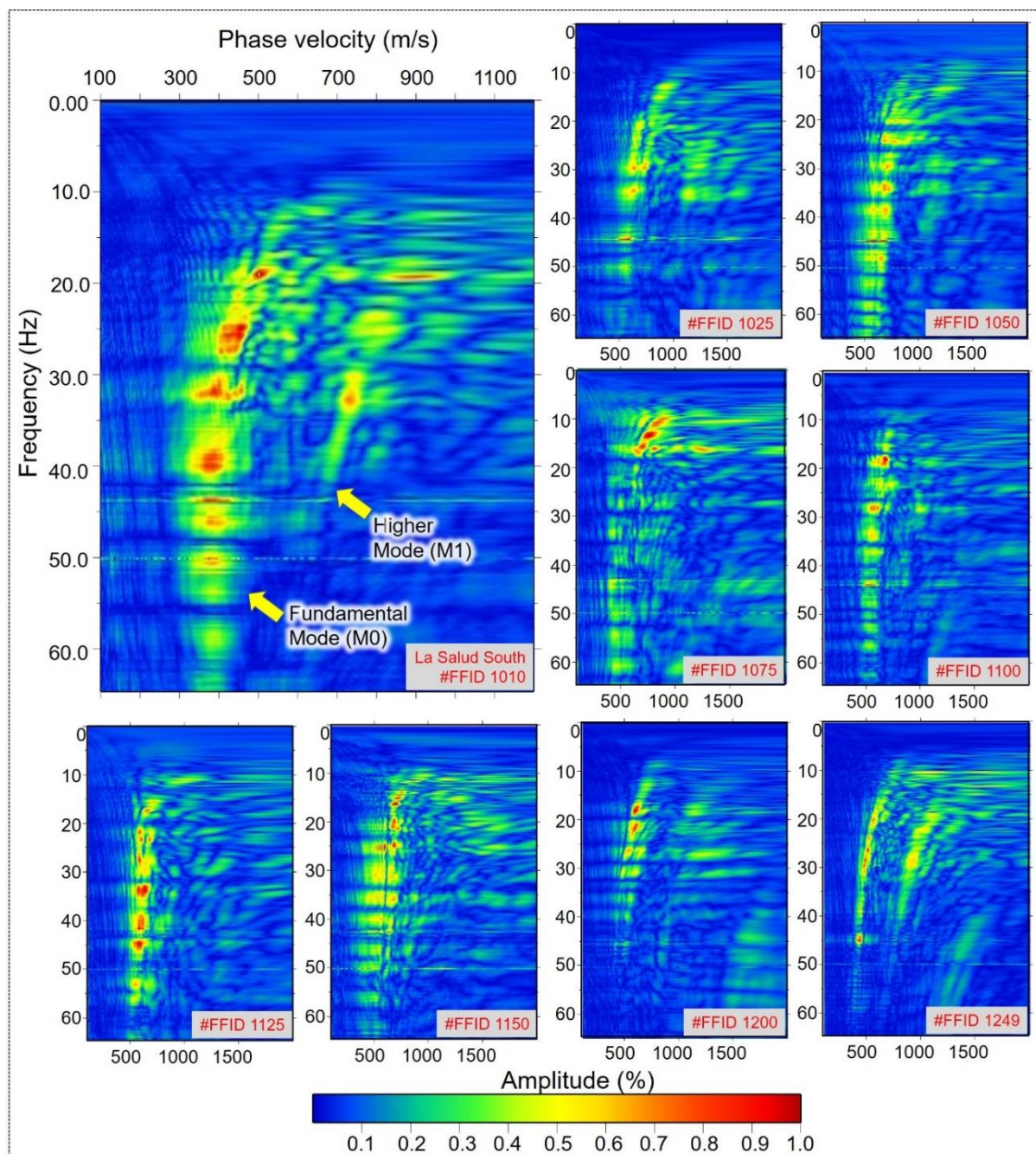


Figure 4.6 The DC of the La Salud South profile.

Fig. 4.7 displays examples of dispersion diagrams belonging to the Carrascoy profile. High amplitudes arise inside this frequency range 5-60 Hz and phase velocity ranging from 300-1500 m/s. In FFID 1010, the dispersion curve corresponding to the fundamental mode of the surface waves in frequency 10-35 Hz can be clearly identified. Higher modes are also visible for example

within the frequency interval 20-30 HZ. These are also identifiable in shot gathers FFID 1250-11350. On the other hand, the dispersion character of the surface waves is not visible on id shot gathers (FFID 1010-1200). In the FFID 1350, the fundamental mode trend follows the interval frequency of 5-20Hz and the first higher mode trend is at frequency of 10-35 Hz.

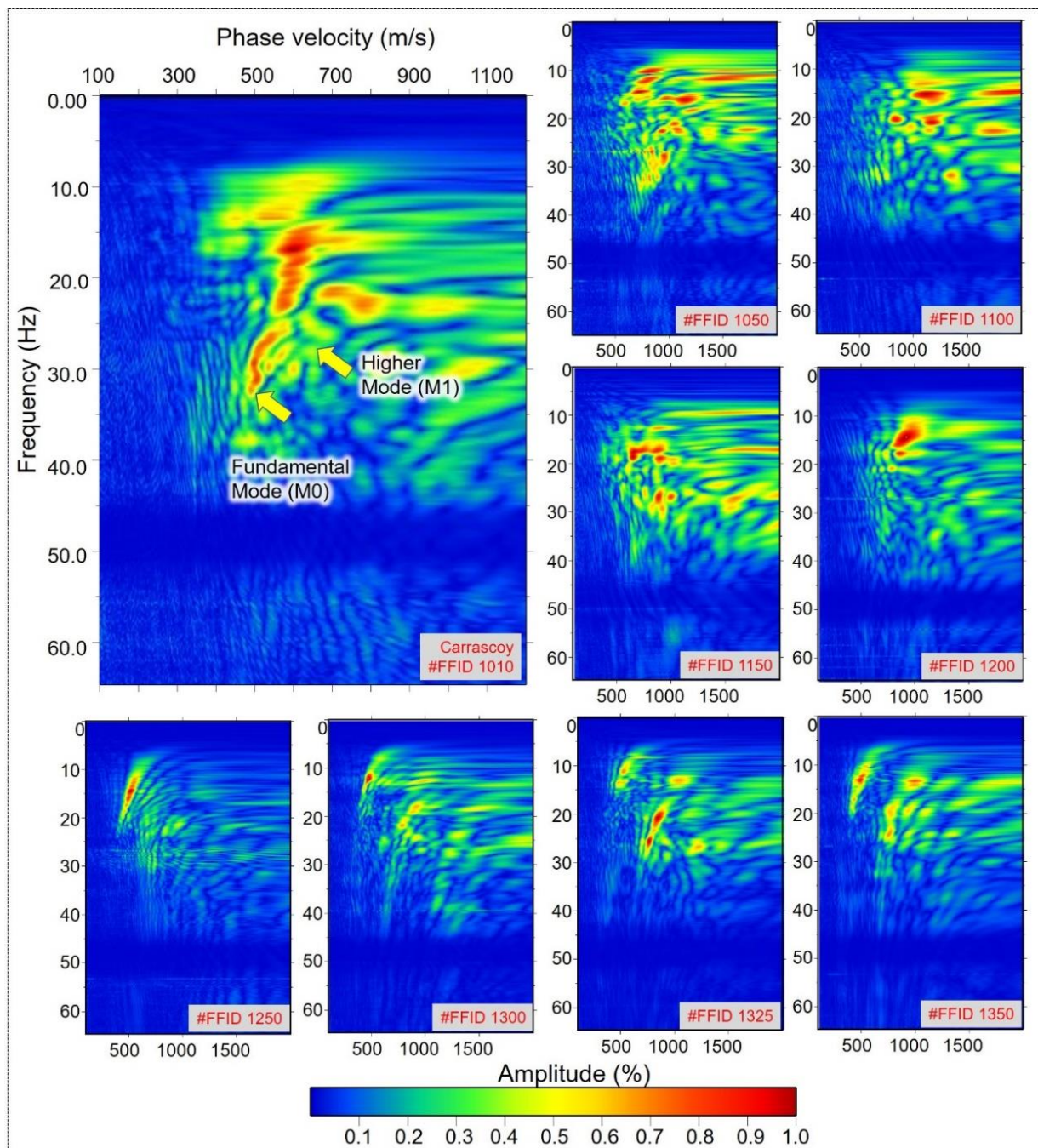


Figure 4.7 Examples of dispersion diagrams of the Carrascoy profile.

4.2.3 Extracting the dispersion curves

After the analysis, the dispersion curves were digitized to obtain the main phase velocity and frequency of the data. After the dispersion curve is generated, the fundamental mode (M_0) of the surface waves was digitized. The picking process was limited to the fundamental mode (V_{ph-f}) following the maximum-amplitude trend was supervised by the operator. The characteristics of the fundamental mode of the dispersion curve are usually the most employed in MASW analysis because it is the easiest to recognize [Park et al., 1999; Xia et al., 2002]. The example of dispersion curves extractions are shown in Fig. 4.8: La Torrecilla survey, Fig. 4.9: La Salud North survey, Fig. 4.10: La Salud South survey; and Fig. 4.11: Carrascoy survey.

Fig. 4.8 shows a few examples of the dispersion diagrams with the picked dispersion curves for a few shot records from the La Torrecilla survey. The maximum for the fundamental mode is picked manually by the operator (black dotted line in Figs. 4.8 to 4.11). The dispersion curve from field measurement is represented by the black dotted line, while the theoretical dispersion curve is represented by the white dotted line. A total of 209 dispersion curves were picked. In FFID 10150, the high-amplitudes reveal a well-defined trend, thus as a result well defined dispersion curves can be selected. Meanwhile, dispersion curve image in FFID 10075 is relatively noisy, and the curve extraction within the frequency band of 10-20 Hz becomes very difficult to identify. However, within the frequency band between 20-50 HZ, the trend of the dispersion curve is quite clear so that the picking process carried out by the operator becomes easier.

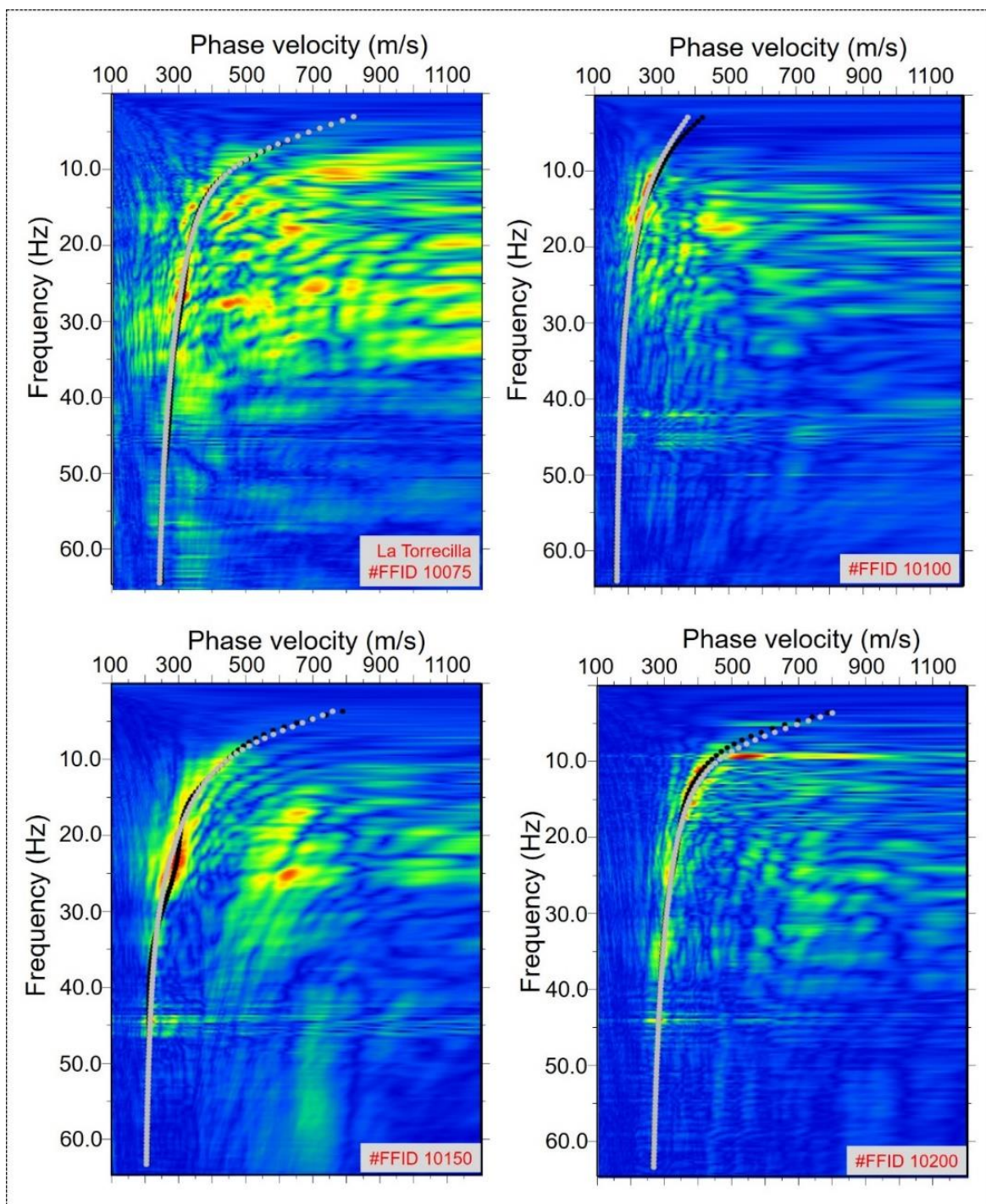


Figure 4.8 Examples of dispersion curves in shot records from the La Torrecilla survey. The black dotted line represents the DC from field measurement, while the white dotted line represents the theoretical dispersion curve.

The dispersion diagrams along the La Salud North profile reveal a well-defined and marked fundamental mode (Fig. 4.9). For this profile a total of 166 dispersion curves were picked. The trend of high amplitude dispersion curve can be easily identified and therefore dispersion curves are well defined in all shot gathers.

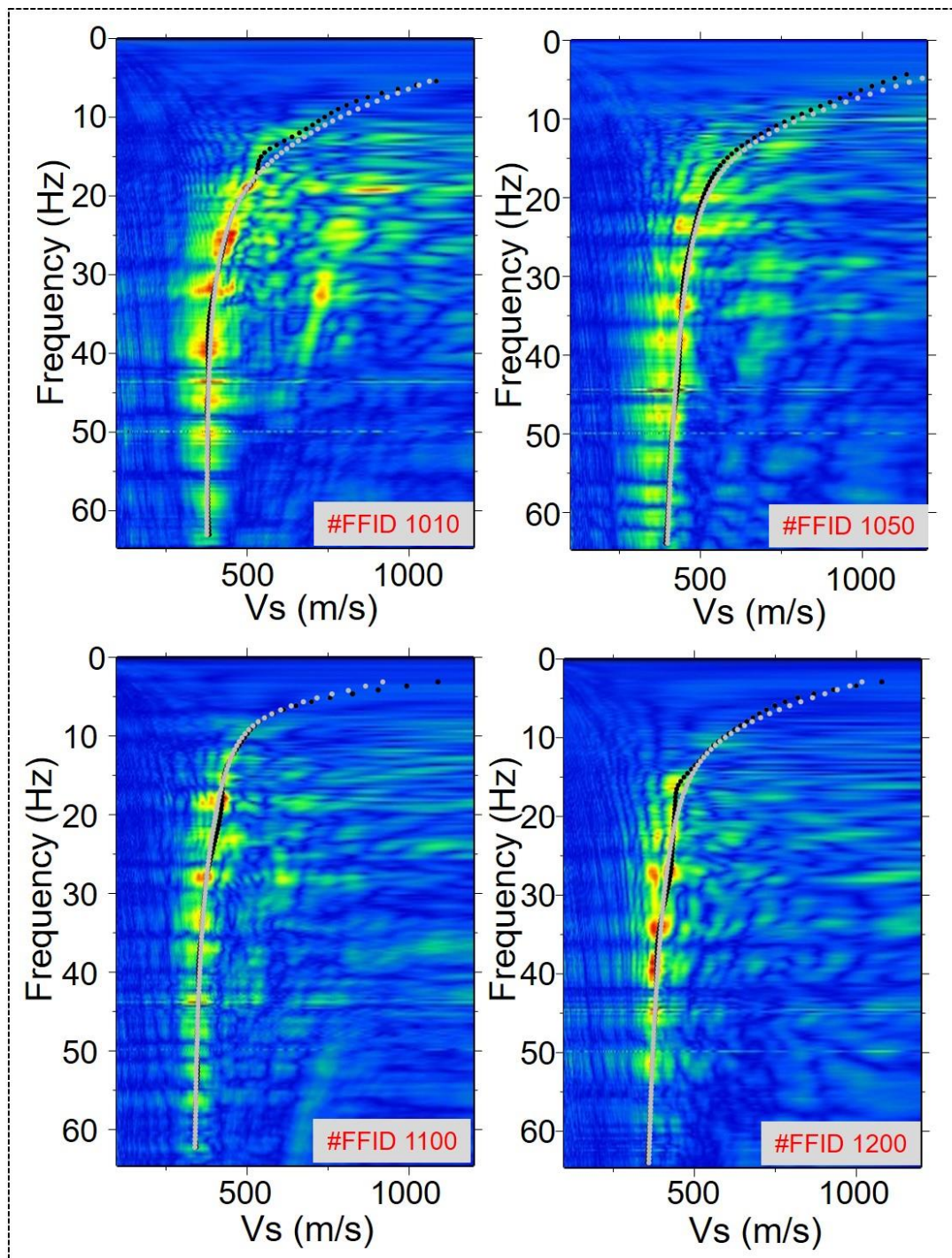


Figure 4.9 The example the dispersion curve in the La Salud North profile.

The resolution of dispersion curve image is clear in the La Salud South profile (Fig. 4.10), making the picking process easier and faster for all frequencies. The high-resolution dispersion curves can be identified in all shot records. A total of 247 dispersion curves were picked and inverted individually.

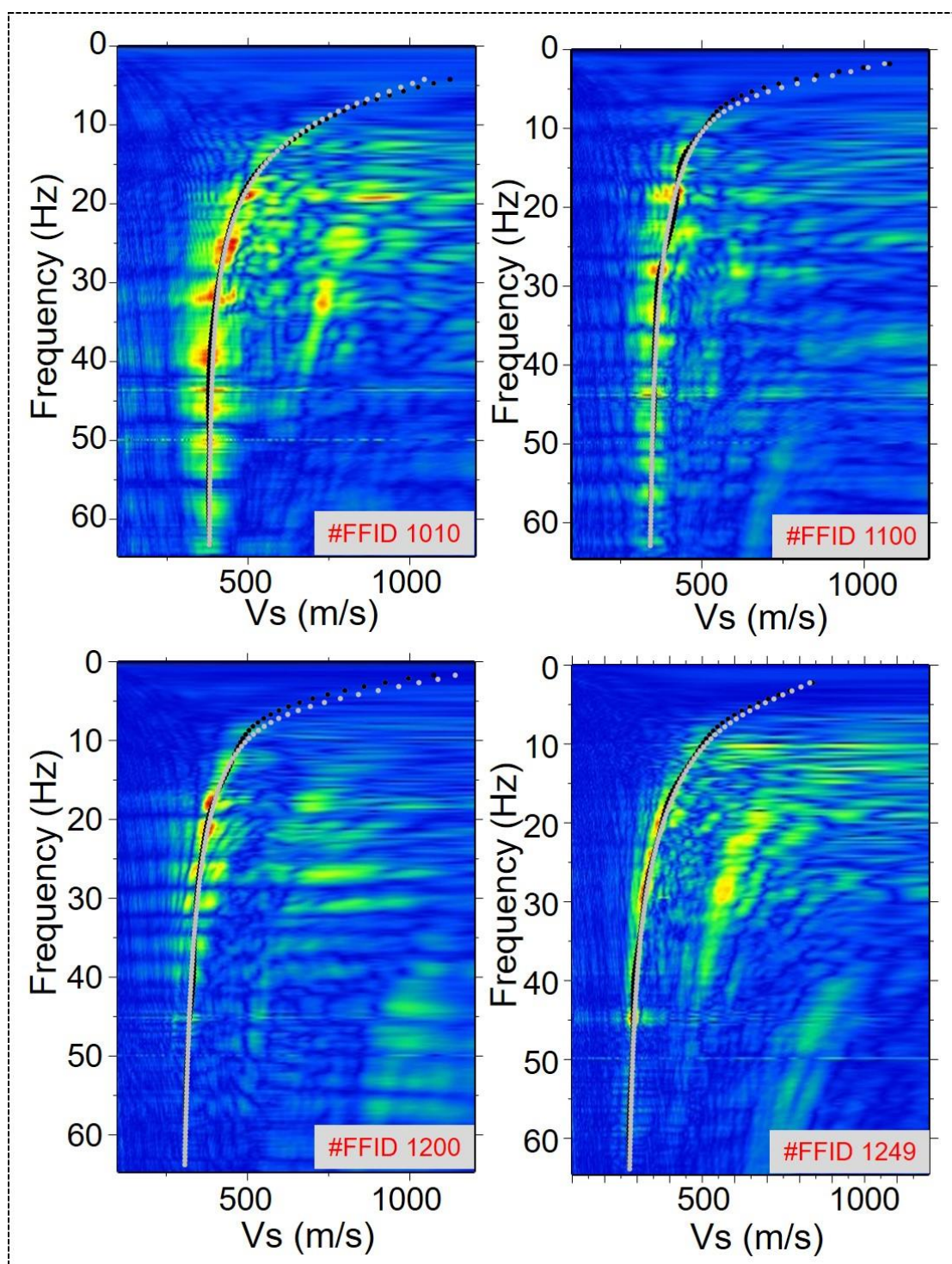


Figure 4.10 The example of the dispersion curved picked for the fundamental model in the La Salud South site.

The resolution of dispersion curve image at the Carrascoy profile is moderate (Fig. 4.11). For example, in FFID 1010, the high amplitude trend of the dispersion curve is clearly marked, similarly for FFID 1250 and, FFID 1300. However, in FFID 1200, the trend of high amplitude at 20-40 Hz frequency is less clear. The operator picked a total of 416 dispersion curves manually.

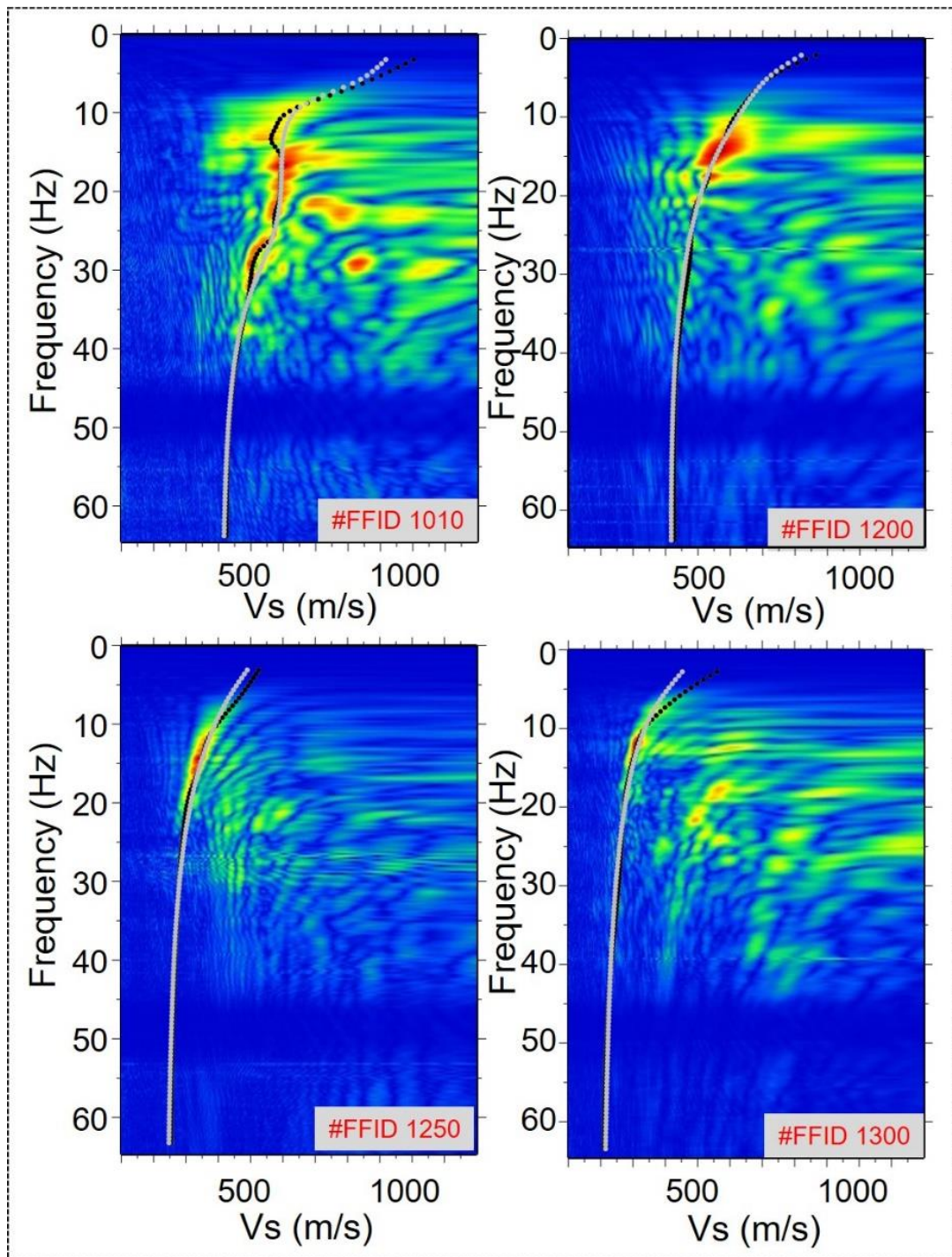


Figure 4.11 The example dispersion curves selected within the Carrascoy transect.

4.3 Inversion

To obtain velocity-depth models along the transects, two steps were needed. In the first a 1D Vs-depth profile was constrained by each dispersion curve using iterative inversion algorithm. The inversion strategy is generally based on minimizing the misfit between observations and synthetic simulations [Tarantola and Vallete 1982; Menke, 1984; Snieder and Trampert, 1999;

Socco et al., 2010] as described in previous chapter. An inversion scheme aiming to retrieve, iteratively a smooth velocity-depth function was used. The model was parameterized, as build-up of a number of homogeneous layers, that is, layers featuring constant physical properties for each layer (Chapter 3). The resulting velocity-depth function, and/or subsurface physical model can be considered to be represented by a series of “ n ” layers with shear wave velocities ($V_{s1}, V_{s2}, \dots, V_{sn}$), densities ($\rho_1, \rho_2, \dots, \rho_n$) and, thicknesses ($t_1, t_2, \dots, t_n$). Through inversion theory [Tarantola and Valette, 1982; Menke 1984; Constable, 1987; Parker 1994] the scheme aims to constrain a model (unknown) that is able to reproduce the observables as closely as possible.

The inversion is nonlinear and thus an iterative approach is devised, guided by constrained optimization algorithms (Eq. 3.16). The difficulties of such schemes are widely discussed in inversion contributions [Menke 1984; Constable, 1987; Parker 1994] and are mostly due to the non-linearities of the problem and/or the non-uniqueness character of its solution. In order to avoid such issues, we considered a strategy (Occam’s Inversion) that aims to favor the simplest (i.e. the smoothest model; Eq. 3.17) that is able to most closely reproduce the measured data [Haney and Qu, 2010]. The inversion process is carried out iteratively, modifying the theoretically obtained V_s profile which has the best match with the experimental results (real data). The iteration process continues until a minimum error (root mean square, RMS) is reached, and new iterations do not produce an improvement in the RMS (in this study, at least six iteration were carried out).

The starting model in this study had a constant velocity half space consisting of a V_s 500 m/s and a density of 2.0 g/cm³ (these values are consistent with the average values of V_s and density of shallow unconsolidated sedimentary rocks). The half-space was divided into layers with a thickness of 0.5 m each, this constant velocity model features 300 layers (all with identical physical properties).

Alternative initial models were tested these where all limited to 300 m depths. However, layer thicknesses ranging from 0.5 to tens of meters where considered, and starting velocities of 150 m/s to 700 m/s. After a number of iterations, the most consistent starting model was considered

to be build by 300 layers of 0.5m thickness down to a depth of 150 m. These stack of constant velocity layers would simulate a constant velocity half space.

The input data used in the inversion algorithm included: the frequency and phase velocity picks as well as the error estimates (error estimation $\sim 10\%$) [Xia et al., 2002; Park and Carnevale, 2010]. The resulting output consists of estimates of V_s velocity and standard deviation as a function of depth. The standard deviation is defined as the inverted velocity's estimated variability. The 1D inverted velocity profiles reach depths down to 150 m (e.g. Fig. 4.12 to Fig. 4.15) but the resolution power of the inversion decreases with depth, as reflected by the systematic increase in the standard deviation of V_s velocity from inversion and model. The illustration displaying the velocities, V_s calculated and theoretical, as well as the corresponding observed and synthetic dispersion curves obtained from a few shot records in each of the profiles are shown in Figs. 4.12 to Fig. 4. 15.

In this study, velocity estimates are considered resolved when their standard deviation is less than 10%, where this value is the average error value that is often used as a standard in the inversion process [Xia et al., 2002; Park and Carnevale, 2010]. This assumption, on average, limits the resulting models down to 150m below the surface. Individual shot gathers were subjected to analysis and inversion, resulting in hundreds of analyses and their corresponding 1D V_s -depth functions. The analyzed shot records feature a 6m spacing, so the resulting 1D V_s -depth functions are assumed to be spaced 6m as well. The highest amplitude contributions to the signal are within the frequency range of 10-45 Hz, therefore velocity estimates are assumed to be velocity averages over a length of 25-35 m (V/f). For each shot record, the output consists of a smooth model and its standard deviation (Fig. 4.12 to Fig.4.15).

Fig 4.12 shows the inversion results consisting of the dispersion curve (observed and theoretical) and the inverted 1D V_s -depth profile in a shot gathers from La Torrecilla profile. This figure shows the velocity model of each particular shot position. The red line is the inverted velocity as the depth function resulting from the inversion. The gray line is the starting velocity

model, which is a single layer characterized by a S-wave velocity of 500 m/s. In La Torrecilla profile, we obtained a total of 209 DC derived from multiple shot gathers to infer 1D and 2D Vs-depth models. The minimum misfit (standard deviation) between theoretical and calculated data in La Torrecilla profile is less than 8%, and it is observed at frequencies ranging 5-60 Hz.

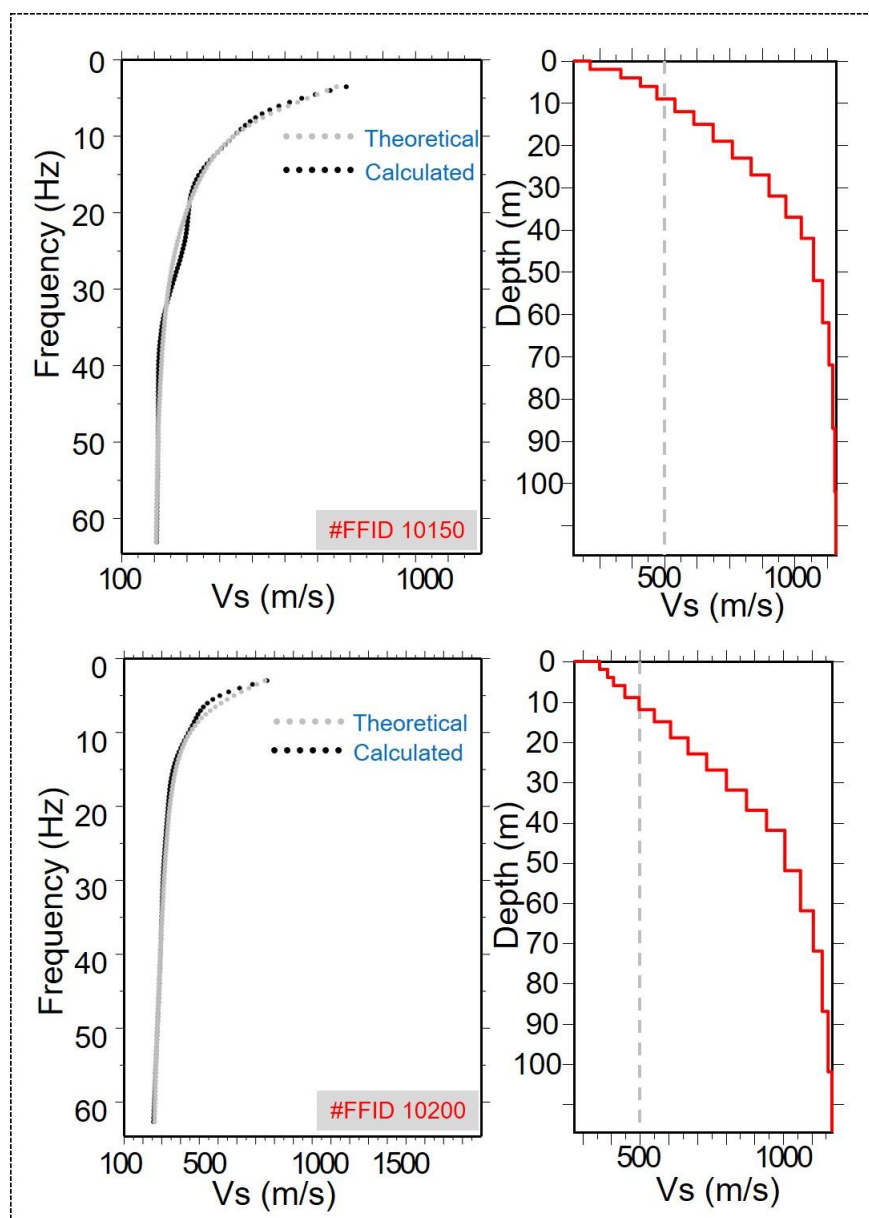


Figure 4.12 The example of dispersion curve (left hand) and 1D Vs-depth profile (right hand) in the La Torrecilla profile. The inverted velocity, the velocity depth function resulting from the 1D inversion, is displayed in red. The gray line in the right panel represents the starting velocity model, which is a single layer with a Vs of 500 m/s. The gray dots in the left panel correspond to the theoretical dispersion curve of the inverted Vs-depth function illustrated in the right panel.

The illustration of extraction DC and 1D Vs-depth profile of the La Salud North site shown in Fig. 4.13 (the shortest profile with the length about 996 m). In La Salud North profile, we extracted a total of 166 dispersion curves derived from multiple shot gathers. The minimum misfit (standard deviation) between the calculated and theoretical in La Salud North profile is less than 10%.

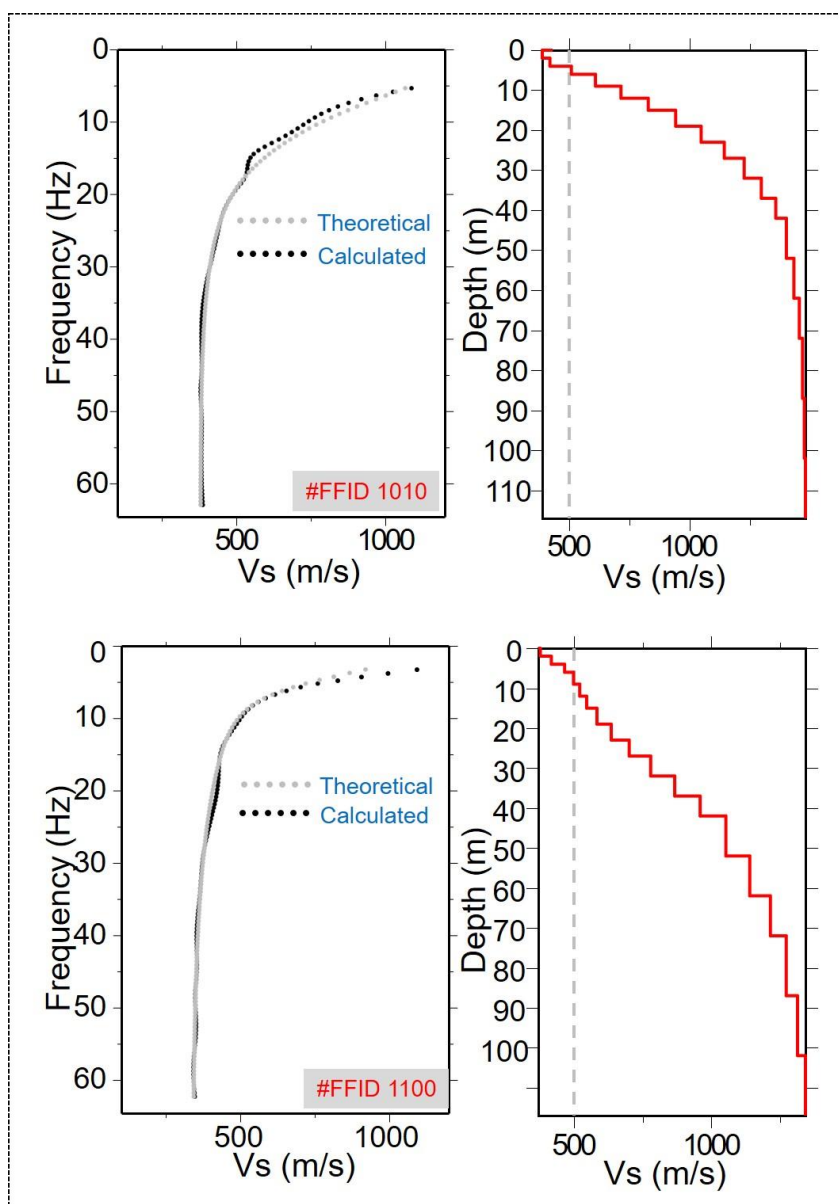


Figure 4.13 The example of extraction dispersion curve and 1D Vs-depth profile in the La Salud North profile.

The illustration of extraction DC and 1D Vs-depth profile of the La Salud South site shown in Fig. 4.14. In La Salud North profile, we extracted a total of 247 dispersion curves derived from

multiple shot gathers to obtain 1D and 2D Vs-depth models. The minimum misfit (standard deviation) between model and observed data is less than 10%.

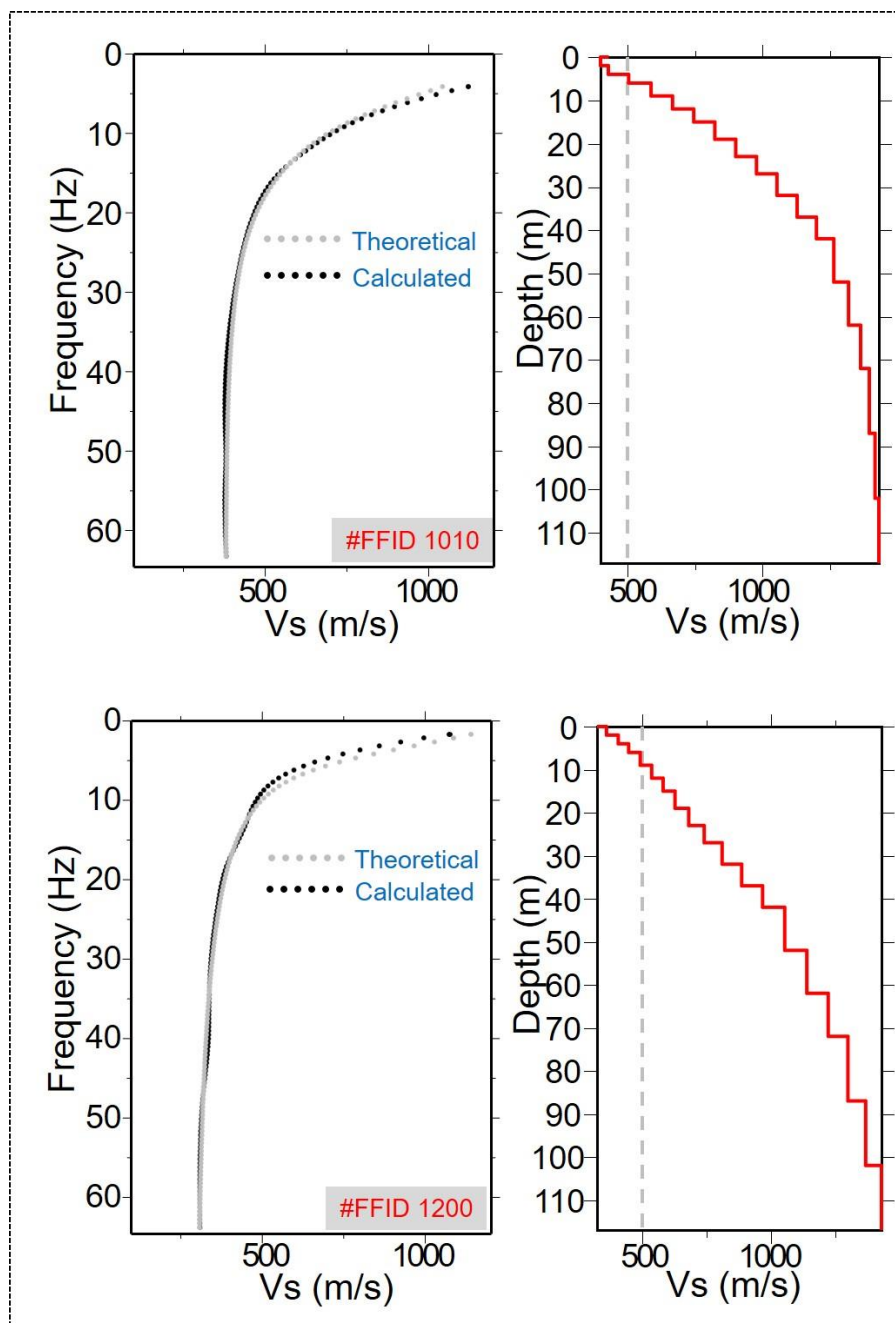


Figure 4.14 The example of extraction dispersion curve and 1D Vs-depth profile in the La Salud South profile.

For the Carrascoy profile (Fig. 4.15), which is the longest profile in this study, we extracted a total of 416 of dispersion curves with the standard deviation less than 12%. Carrascoy profile is the longest seismic transect in this survey, the length of the Carrascoy profile is approximately 2496 m.

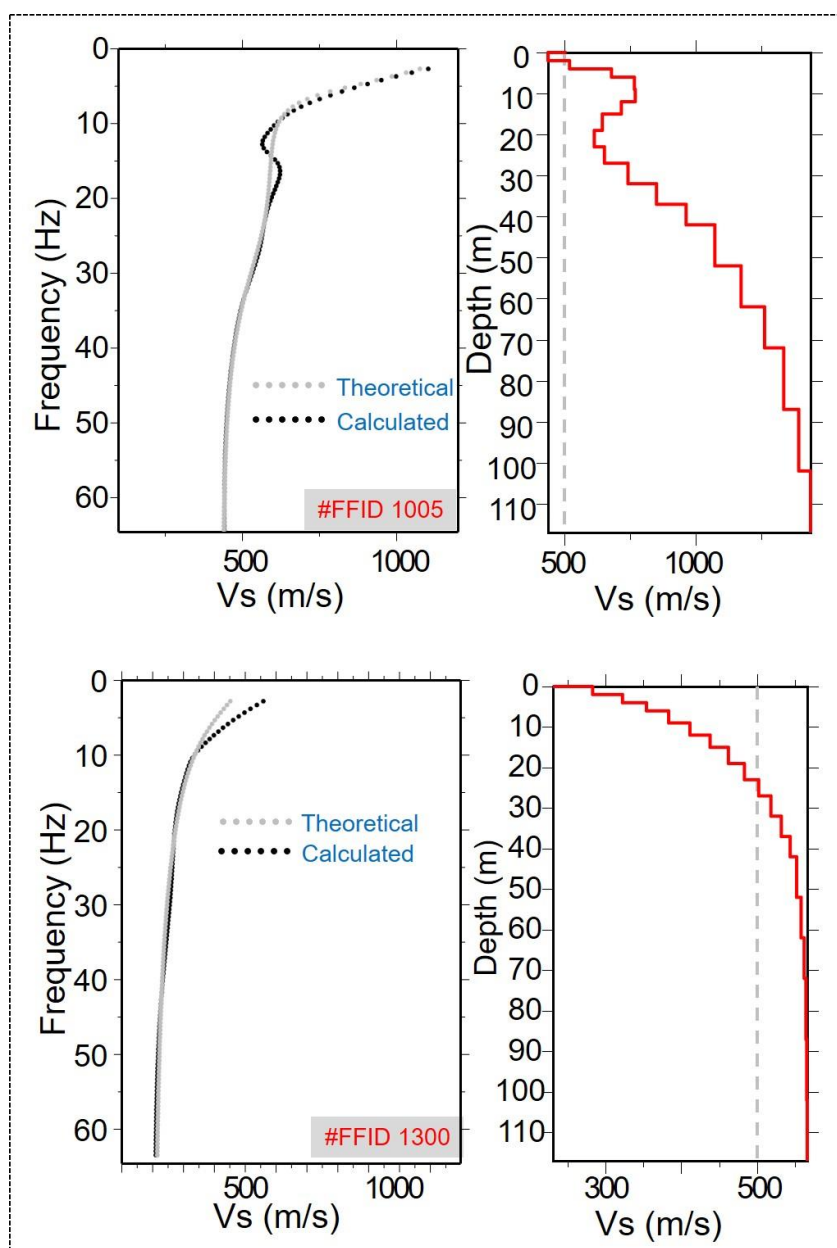


Figure 4.15 The example of extraction dispersion curve and 1D V_s -depth profile in the Carrascosy profile.

Once the respective 1D velocity-depth functions for each shot record were obtained, they were pasted together to create a 2D V_s -depth model using shot gathers geometry along the profile. To average spatially balance small-scale sharp anomalies, a spatial smoothing operator was applied to the 2D velocity model (Haney and Qu, 2010; Key, 2009; Werthmüller, 2017). This operation is justified by the fact that the inverted model is an average estimate over a wavelength of 25-35 m that integrates the frequency of the seismic signal and the offset contributions.

Furthermore, each velocity-depth function is the smoothest model able to produce the observations dispersion curve within 10% standard deviation.

For surfaces that vary due to differences in elevation. Topographic elevation information was also taken into account in the V_S depth model. The results of 2D V_S -depth profiles of the study area are shown in Fig. 4.16. The profiles provide reliable information of down to 150m depth and reveal S- wave velocity layers that are subparallel to the surface. The V_S varies in the range of 200-2000 m/s, which is represented by the color scale (hot colors indicate low velocities and cool colors indicated high velocities).

In the La Torrecilla profile (Fig. 4.16a), the value of the V_S model is relatively sub-parallel with the velocity layer 200-600 m/s in the near the surface. At the elevation of 350-450 m, a lower velocity is located in the center of the profile with values between 600-800 m/s, in contrast to the left and right sides of the model which present higher velocities within 800-1000 m/s.

In the La Salud North profile (Fig. 4.16b), the velocity layers are parallel to the surface with the velocity layer 200-600 m/s. In elevation 300-450 m, the velocity layer is 800-1100 m/s, and more 1100 m/s below the elevation 300 m. The velocity distribution in the La Salud South profile (Fig. 4.16c) is comparable to that in the La Salud North profile, but there is a low-velocity zone located near the center (FFID 1070-1120) and near the right-hand of the profile (FFID 1200 to the end of SE direction). Finally, the velocity layers of the Carrascoy site (Fig. 4.16d) are also subparallel to the surface with low-velocity layer 200-600 m/s. There is a low-velocity layer at FFID 1230-1380 and a relatively high-velocity zone beneath FFIDs 1001-1190 and FFIDs 1250-1350.

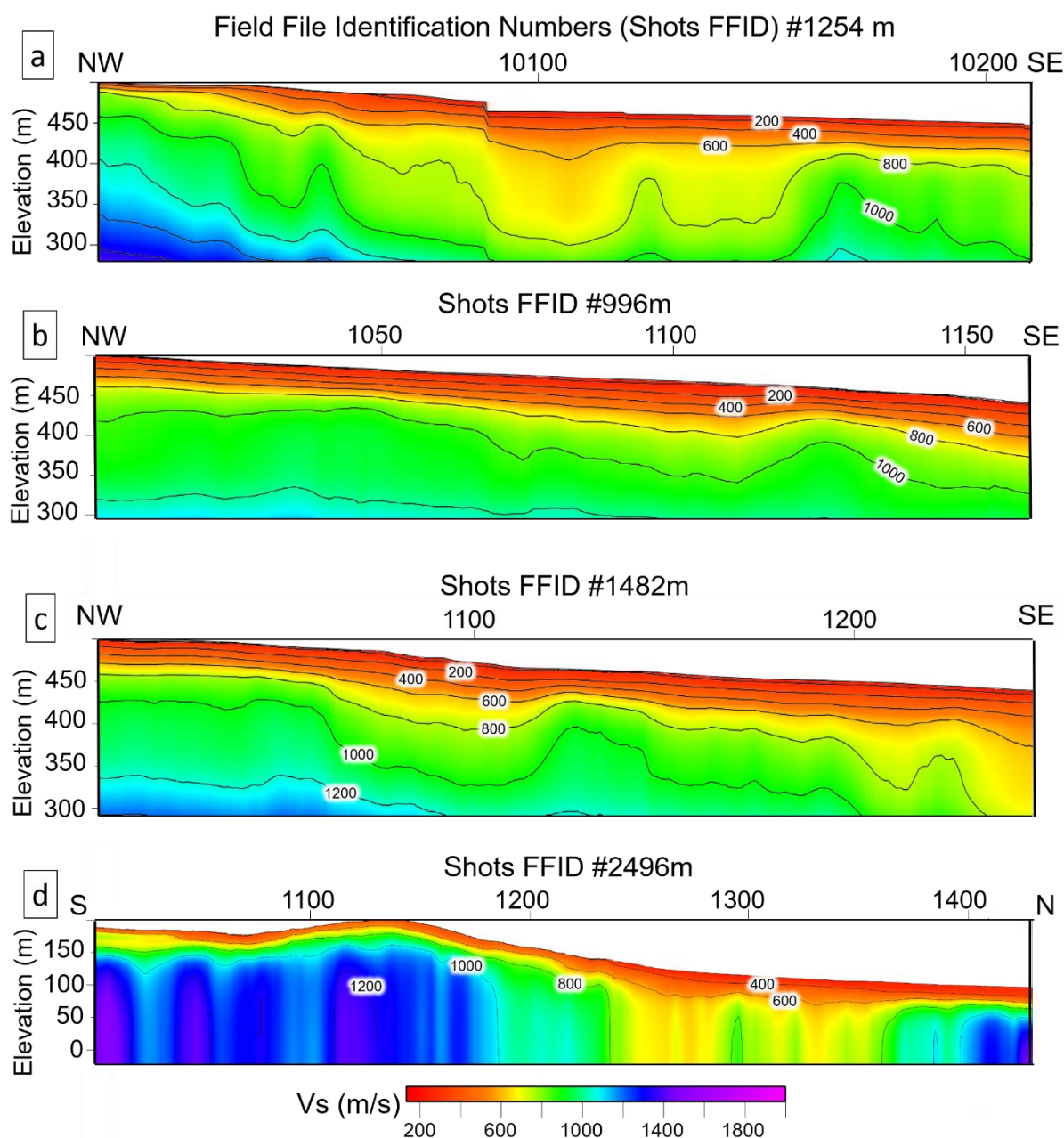


Figure 4.16 The result of 2D V_s -depth profile. a) the La Torrecilla profile, b) the La Salud North profile, c) the La Salud South profile, and d) the Carrascoy profile.

4.4 P- wave tomography

The inversion schemes used of the first arrival travel times were described in the previous chapters. It must be emphasized that two approaches were tested one consisted in using an academic software package, the 3D tomographic algorithm known as Pstomo_eq [Tryggvason et al., 2002]. The second approach was provided by a commercial software package built using the “Deltat-T-V” 1D inversion code (see chapter 3, section 3.2.3 for a description). The latter performs

a nonlinear smooth inversion of the travel times through a layer stripping scheme in the CMP domain.

The commercial seismic processing software package “Globe Claritas”, was used to pick the first arrivals travel times for the P-wave tomography investigation (Fig. 4.17). Due to the high quality of the recorded data, we were able to retrieve 90% of the first arrival travel times, which cover all possible offset ranges, up to 480 m (maximum offset), this relatively long offset is sufficient to be able to resolve Velocity models down to 200 m depth, comparable to the velocity models resolved by the MASW analysis. This high percentage of successfully picked first arrival ensures good lateral and depth resolution for the first 150 m, including locations with some anthropogenic activity-related noise (e.g. traffic).

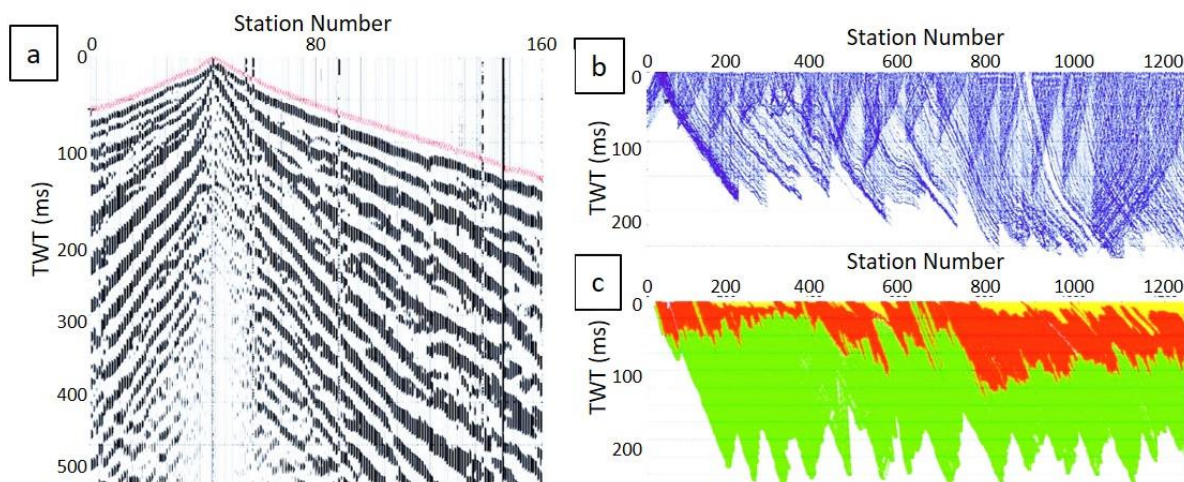


Figure 4.17. The basic inputs for resolving the P-wave velocity subsurface features. a) Example of the first-arrival times picked in the shot viewer (red crosses) in Carrascoy profile; b) the space-time graphs of all picked first-arrivals; and c) the first-arrival time are picked as a function of the independent variables CMPx (station) and the CMP constant offset. Ray paths are shown with a velocity re-duction of 5000m/s.

Overall, in Fig. 4.18, the low velocities are closed to the surface (sub-parallel to the surface) and the higher velocity layer is located at deeper levels. The velocity interval near the surface is about 900-100 m/s and the high velocity layer is about 3500-3700 m/s in the deepest layer. These relatively high values might be indicative of the more consolidated nature of the deeper rocks. In

La Torrecilla profile (Fig. 4.18a), the low velocity layer (< 1300 m/s) is located along the profile and thickens in the middle of the track at a distance of *ca.* 450-700 m. In La Salud North profile (Fig. 4.18b), the low velocity layer thickens on the NW side at a distance of *ca.* 150-300 m. In contrast, in the La Salud South profile (Fig. 4.18c), the low velocity layer thickens on the SE side at a distance of *ca.* 1200-1400 m. Then, the low velocity layer thickens. seen thickening at a distance of *ca.* 1500-2000 m on the Carrascoy profile (Fig. 4.18d).

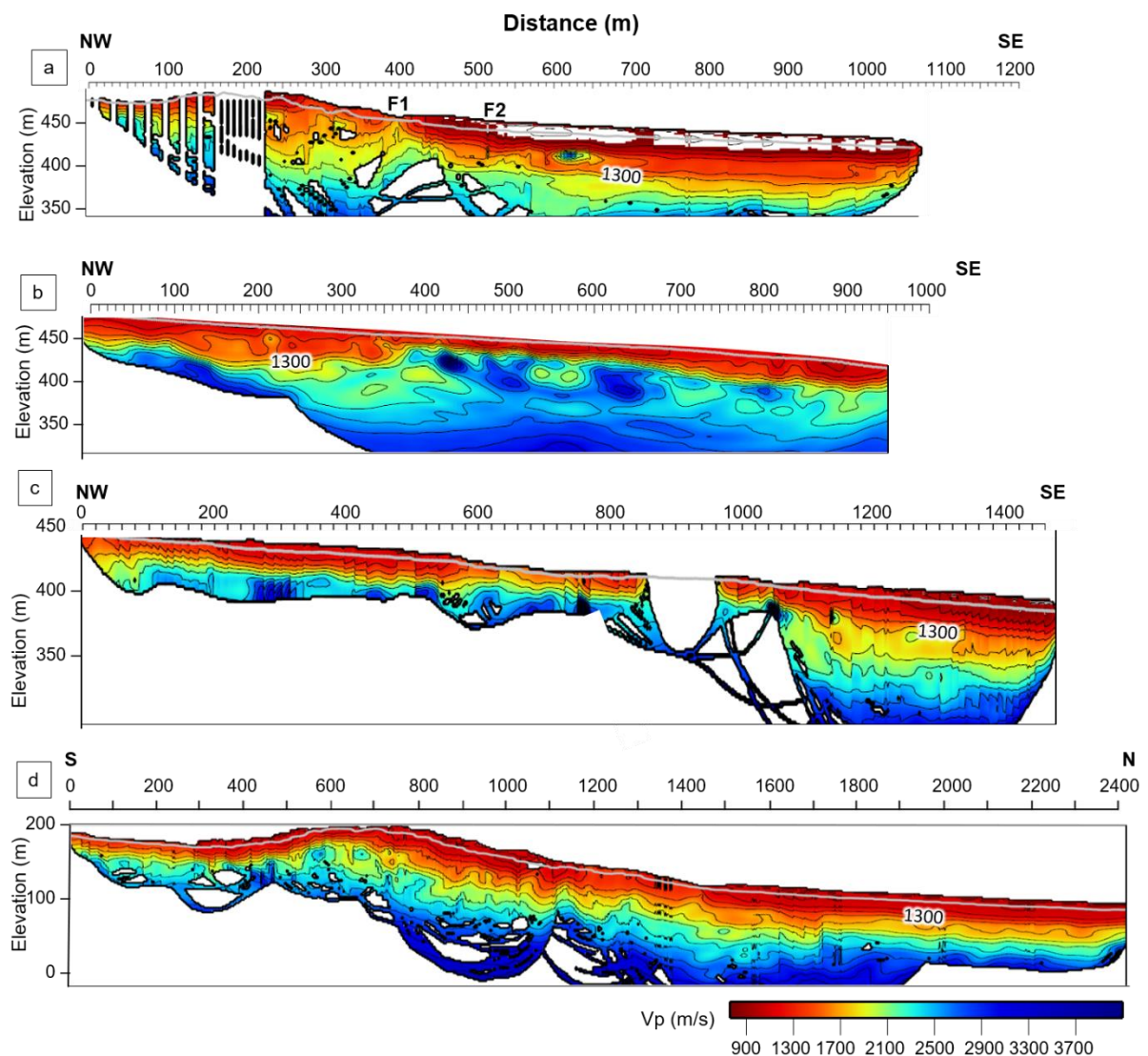


Figure 4.18. The P- wave velocity depth profile from seismic tomography. a) the La Torrecilla site, b) the La Salud North site, c) the La Salud South site, and d) the Carrascoy site. Note that the curved elements in the 2D velocity models presented in this figure correspond to the ray paths that sample the model. The white areas inside the models are indicative of zones where a velocity value was not retrieved with sufficient confidence.

CHAPTER 5
Characterization of the shallow subsurface structure across
the Carrascoy Fault System (SE Iberian Peninsula)
using P-wave tomography and Multichannel Analysis
of Surface Waves

“You cannot teach a man anything, you can only help him discover it in himself.”
— Galileo Galilei

Characterization of the shallow subsurface structure across the Carrascoy Fault System (SE Iberian Peninsula) using P-wave tomography and Multichannel Analysis of Surface Waves

H. Handoyo^{1,2,3} I. DeFelipe⁴ R. Martín-Banda⁵ J. García-Mayordomo⁵ D. Martí⁶ J.J. Martínez-Díaz⁷ J.M. Insua-Arévalo⁷
T. Teixidó⁸ J. Alcalde¹ I. Palomeras⁴ R. Carbonell¹

¹Geosciences Barcelona (GEO3BCN, CSIC)
Barcelona, Spain. Handoyo E-mail: handoyo.geoph@tg.itera.ac.id

²Teknik Geofisika, Institut Teknologi Sumatera
South Lampung, Indonesia

³Departament de Dinàmica de la Terra i de l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona
Barcelona, Spain

⁴Departamento de Geología, Universidad de Salamanca
Salamanca, Spain

⁵Instituto Geológico y Minero de España (IGME-CSIC)
Madrid, Spain

⁶Lithica SCCL
Santa Coloma de Farners, Girona, Spain

⁷Department of Geodynamics, Stratigraphy and Paleontology, Universidad Complutense de Madrid
Madrid, Spain

⁸Instituto Andaluz de Geofísica y Prevención de Desastres Sísmicos, Universidad de Granada
Granada, Spain

| ABS TRACT |

The seismicity in the SE Iberian Peninsula is distributed parallel to the coast in a well-developed strike-slip fracture system known as the Eastern Betic Shear Zone (EBSZ). This work focuses on the characterization of the shallow subsurface structure of the Algezares-Casas Nuevas Fault, within the Carrascoy Fault System of the EBSZ. The Carrascoy Fault borders the Guadalentín Depression to the south, which is a densely populated area with extensive agricultural activity. Therefore, this fault system represents a seismic hazard with significant social and economic implications. We have constructed two velocity-depth models based on P-wave tomography and Multichannel Analysis of Surface Waves (MASW) acquired from seismic reflection data. The resulting velocity models have allowed us to interpret the first ~250m depth and have revealed: i) the thickness of the critical zone; ii) the geometry of the Algezares-Casas Nuevas Fault; iii) the depth of the Messinian/Tortonian contact and iv) the presence of blind thrusts and damage zones under the Guadalentín Depression. Our results have also helped us to estimate an apparent vertical slip rate of 0.66 ± 0.06 m/ky for the Algezares-Casas Nuevas Fault since 209.1 ± 6.2 ka. Our results provide a methodological and backflow protocol to study the shallow subsurface of active faults, complementing previous geological models based on paleoseismological trenches, and can be used to improve the seismic hazard assessment of tectonically active regions around the world.

KEYWORDS | Algezares-Casas Nuevas Fault. Carrascoy Fault. Frontal Strands Fault. MASW. P-Wave Tomography.

INTRODUCTION

High-resolution seismic imaging of the subsurface is a long-established technique for fault detection (Ivanov *et al.*, 2006; Mansfield and Cartwright, 1996), which is a challenging task due to near-surface effects, strong lateral velocity contrasts across steeply dipping structures, presence of soft soils, velocity inversions and/or fault-zone heterogeneities, among others (e.g. Alcalde *et al.*, 2013; Bruno *et al.*, 2010; Catchings *et al.*, 2014; Improta and Bruno, 2007). Despite those difficulties, these studies provide very valuable information about the shallow subsurface structure in active tectonic zones, allowing to characterize fault zones and their associated structures, map blind faults and damage zone areas, image colluvial wedges (Improta and Bruno, 2007; Mattson, 2004; Villani *et al.*, 2017), and to define the depth of the critical zone (e.g. Handoyo *et al.*, 2022; Parsekian *et al.*, 2015).

An interesting area to study the shallow subsurface structure of active faults is the Eastern Betic Shear Zone (EBSZ), in the SE of the Iberian Peninsula (Fig. 1A, B). The EBSZ is an approximately 450km long network of NE-SW-oriented faults (Banda and Ansorge, 1980) that runs parallel to the coast of the Mediterranean Sea (De Larouzière *et al.*, 1988; Silva *et al.*, 1993; Silva, 1994). The EBSZ is considered the most active fault system in the Iberian Peninsula (García-Mayordomo, 2005; García-Mayordomo *et al.*, 2007; Gómez-Novell *et al.*, 2020). This area is characterized by an intense earthquake activity which has caused significant damage during historical times (e.g. Gómez-Novell *et al.*, 2020) (e.g. the 1518 AD Vera (VII-IX) (e.g. Silva *et al.*, 2003); 1522 AD Almería (IX) (e.g. Gràcia *et al.*, 2006) and 1829 AD Torrevieja (IX-X) (e.g. Alfaro *et al.*, 2002) earthquakes; Fig. 1A, B). One of the most recent and destructive earthquakes took place on the 11th of May 2011. It had a Mw of 5.1 and affected the city of Lorca causing severe damage and 9 fatalities. The earthquake was rapidly located and associated to the Alhama de Murcia Fault (Martínez-Díaz *et al.*, 2012a, b; Vissers and Meijninger, 2011), an oblique reverse fault that cuts across the city of Lorca and extends for ca. 100km in a NE-SW direction (Martínez-Díaz, 2002, 2019; Masana *et al.*, 2004; Sanz de Galdeano *et al.*, 2020) (Fig. 1A, B). However, the Alhama de Murcia Fault is not the only structure that represents a seismic hazard in that area. To the south of the Guadalentín Depression, the Carrascoy and Algezares-Casas Nuevas Faults (Fig. 1B, C) also represent a major threat for the city of Murcia and other populations nearby (García-Mayordomo *et al.*, 2007; Gaspar-Escribano *et al.*, 2008; Gómez-Novell *et al.*, 2020), as well as to the agricultural industry. Specifically, for the city of Murcia the official seismic hazard map of Spain shows a peak ground acceleration on the rock of 0.23g with a 10% probability of exceedance in 50 years (475-year return period) (Instituto

Geográfico Nacional-Universidad Politécnica de Madrid (IGN-UPM), 2013).

Despite the great amount of works carried out in the EBSZ, the shallow subsurface geometry of the southern border of the Guadalentín Depression, remains uncertain, a matter that is of paramount importance for producing reliable models for seismic hazard assessment. Revealing its subsurface characteristics, locating fault strands at depth and identifying blind faults, can help to understand its structure and how it accommodates the deformation. The INTERGEO project, supported in 2013 by the Spanish research program, was conceived to unravel the morphology of different active faults of the EBSZ by the acquisition of six high-resolution controlled source multichannel seismic transects. Here, we show the model obtained from one of these lines, which samples the Algezares-Casas Nuevas Fault, an oblique reverse fault formed in a strike-slip regional context (Martín-Banda, 2020; Martín-Banda *et al.*, 2016, 2021; Rodríguez-Escudero *et al.*, 2014).

The tectonic relevance of active faults makes them singular targets for high-resolution seismic imaging approaches. Faults and related damage zones feature variations in the physical properties that can be sensed by seismic methods (Ando and Yamashita, 2007; Iacopini *et al.*, 2016; Martí *et al.*, 2006b). Large-scale fault zones can be studied by assessing the changes of the elasticity properties across the fractured area. If the contrast in physical properties at both fault blocks is strong enough, the volume, geometric distribution and extent of these structural elements can be traced by indirect seismic methods. Geophysicists have been using surface waves to characterize the subsurface at a variety of scales; from the entire lithosphere (e.g. Palomeras *et al.*, 2017), to high-resolution near-surface studies (e.g. Socco *et al.*, 2010). Specifically, at our scale of interest (i.e. a few hundreds of meters), the Multichannel Analysis of Surface Waves (MASW) is perhaps one of the most extensively used schemes for subsurface characterization (Foti *et al.*, 2018; Ivanov *et al.*, 2006; Miller *et al.*, 2000; Park *et al.*, 1999; Xia *et al.*, 1999, 2000, 2002). The MASW method has been applied to detect a wide range of subsurface features, and it has proven to be successful in other regions worldwide, reaching a resolution depth 1m to >50m (Ivanov *et al.*, 2006; Miller *et al.*, 2000). Complementary, seismic tomography inverts first arrival travel times to generate the P-wave velocity distribution in the subsurface. This technique is broadly used to unravel the seismic velocity structure of faults showing recent activity (e.g. Feenstra *et al.*, 2016) as well as to image colluvial wedges associated to paleoearthquake surface ruptures, much deeper than the range reached by standard paleoseismic trenches (Gaždová *et al.*, 2015).

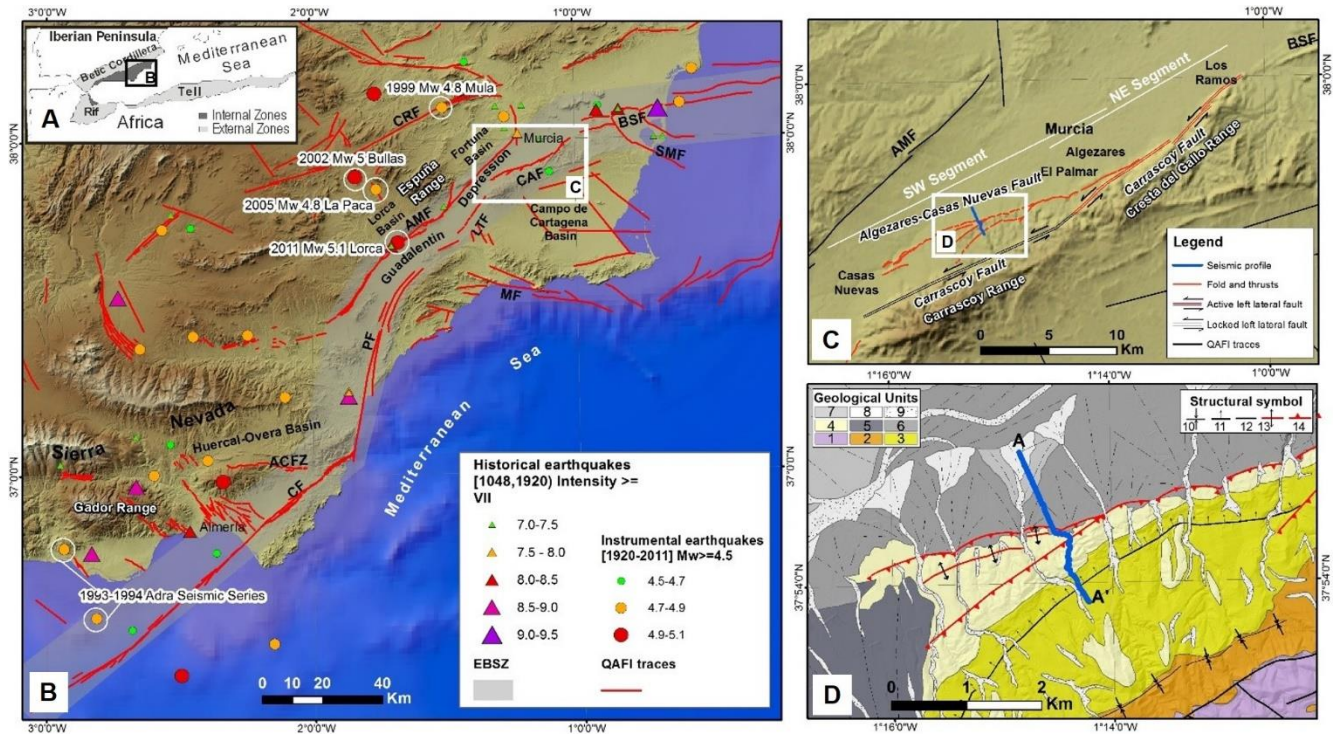


FIGURE 1. A) Regional geological setting of the study area. B) Tectonic map of the EBSZ: Eastern Betic Shear Zone (gray shaded); BSF: Bajo Segura Fault; CAF: Carrascoy Fault; LTF: Los Tollos Fault; AMF: Alhama de Murcia Fault; PF: Palomares Fault; CF: Carboneras Fault; over General Bathymetric Chart of the Oceans (GEBCO) world map in Geotiff Format (ED50/UTM Zone 30° N Projection). Fault traces are from an updated version of Quaternary Active Faults Database of Iberia (QAFI) database (Instituto Geológico y Minero de España (IGME), 2015; García-Mayordomo et al., 2012, 2017). Earthquake data corresponds to a declustered version of the Spanish national seismic catalog (Instituto Geográfico Nacional (IGN), 2011; Instituto Geográfico Nacional-Universidad Politécnica de Madrid (IGN-UPM), 2013). The white circles show the identification of major historical earthquakes and seismic events recorded in the area, cited in the text. C) Detailed tectonic map of the Carrascoy Fault (CAF) and location of the studied seismic profile (blue line). D) Geological map of the studied seismic profile (A-A'). Legend: 1. Internal Zone of the Betic Cordillera; 2. Tortonian; 3. Messinian; 4. Pliocene-Middle Pleistocene (Unidad Roja); 5. Middle Pleistocene. Alluvial fans (1st generation); 6. Middle-Upper Pleistocene. Alluvial fans (2nd generation); 7. Upper Pleistocene-Holocene. Alluvial fans (4th generation); 8. Holocene. Alluvial fans (5th generation); 9. Holocene. Alluvial and valley floor deposits; 10. Syncline; 11. Monocline; 12. Fault; 13. Anticline; 14. Active thrust.

To unravel the near-surface structure across the Algezares-Casas Nuevas Fault we present here a P- and S-wave seismic velocity (V_p and V_s , respectively) depth profiles based on P-wave velocity tomography and MASW. We have established a MASW processing and interpretation flow to obtain reliable V_s models that combined with the P-wave velocity tomography study provided accurate models of the subsurface down to ca. 250m. The resulted V_p and V_s models provide new constraints on the structure of the Algezares-Casas Nuevas Fault, the location of blind faults, the alluvial thickness in the Guadalentín Depression and the depth of the stratigraphic contacts. Finally, in this contribution we thoroughly examined the results of 1D S-wave velocity and 2D pseudo-S-wave velocity from the surface waves inversion that combined with the P-wave tomography method to characterize the shallow subsurface structures in an active fault system. This detailed analysis allowed us to assess the extent to which this method combination can be used to successfully characterize geological features in the subsurface, which is critical to improve seismic hazard assessments in this type of active areas.

GEOLOGICAL SETTING

The EBSZ is the longest fault system of the Betic Cordillera (Fig. 1A), which together with the Tell Fold Belt in north Africa, accommodates the convergence between the Nubian and Eurasian plates since the late Neogene (DeMets et al., 2015; De Larouzière et al., 1988).

At the end of the Messinian-beginning of the Pliocene, the tectonic convergence under a NNW-SSE regional shortening direction (DeMets et al., 2015; Echeverría et al., 2011; Khazaradze et al., 2008; De Larouzière et al., 1988) inverted previous Neogene basins, and the Guadalentín Depression, or tectonic valley (Sánchez-Roldán et al., 2021), formed with a NE-SW orientation in an area that was previously uplifted (De Larouzière et al., 1987; Montanari et al., 1987; Vissers and Meijninger, 2011). This regional shortening direction has kept steady in the region since the late Miocene (Martínez-Díaz, 2002) to the present, as evidenced either by sea-floor magnetic anomalies (e.g. DeMets et al., 2015) or GPS data (e.g. Argus et al., 2010).

The current tectonic regime explains the fault kinematics and the strike-slip and normal component of the active faults in the area (Sánchez-Roldán *et al.*, 2021).

The study area is located in the northern part of the EBSZ (Fig. 1B). There, the Guadalentín Depression is bordered to the north by the Alhama de Murcia Fault and to the south by the complex Carrascoy Fault system, a 33km long NE-SW structure (Silva, 1994). The Carrascoy Fault System is formed by two overlapping segments, with different geometrical, structural and kinematic characteristics (Martín-Banda *et al.*, 2016). The NE segment extends in a N50E trend for 16km between Los Ramos and El Palmar villages and controls the location of the Cresta del Gallo Range (Fig. 1C). The SW segment is more complex, represented by: i) the Carrascoy Fault, that uplifted the Carrascoy Range and ii) the Algezares-Casas Nuevas Fault, that runs for 23km from the villages of Algezares to Casas Nuevas (Fig. 1C). The Carrascoy Fault is a sub-vertical fault with a general left-lateral strike-slip kinematics and the Algezares-Casas Nuevas Fault develops as a low-angle oblique reverse fault (Martín-Banda *et al.*, 2016). The surface geology and the information derived from geomorphological mapping, morphotectonic analysis and paleoseismological trenches performed along the Carrascoy Fault System, revealed the existence a system of thrusts related to the Algezares-Casas Nuevas Fault and transported to the north since 209.1 ± 6.2 ka (Martín-Banda *et al.*, 2016; Martín-Banda, 2020; Martín-Banda *et al.*, 2021). The Algezares-Casas Nuevas Fault constitutes the currently active front of the Carrascoy Range whose development progressively moves to the NW (Martín-Banda *et al.*, 2016) forming a fault propagation anticline. The study profile, located at the southeastern border of the Guadalentín Depression (A-A' in Fig. 1D), samples the

Algezares-Casas Nuevas Fault where it shows two strands, referred as F1 and F2.

The oldest rocks cropping out along the study profile (Fig. 1D) correspond to the metamorphic basement of the Internal Zone of the Betic Cordillera, located in the highest part of the Carrascoy Range. Towards the north, bordering the main relief, upper Miocene marine sedimentary rocks (marl, biocalcarenite and limestone) crop out divided into two units of Tortonian and Messinian age. Along and parallel to the Algezares-Casas Nuevas Fault, a band of Pliocene-middle Pleistocene continental deposits (conglomerate, gravel, sand, marl, and limestone) is deformed in the hanging wall of this fault. These Pliocene-middle Pleistocene deposits are locally known as the Unidad Roja (Jerez *et al.*, 2015) and are considered to be old alluvial fans coming from the erosion of the higher parts of the Carrascoy Range. The youngest materials are middle Pleistocene to Holocene alluvial deposits that fill the Guadalentín Depression. They were deposited during five generations of alluvial fan systems, intercalated with valley floor deposits, glaciais and endorheic deposits (*e.g.* Martín-Banda *et al.*, 2016), constituting an example of the transition from alluvial to fluvial sedimentary systems (Silva, 2014).

METHODOLOGY

The seismic data acquisition was designed to characterize the structure of the Algezares-Casas Nuevas Fault at depth. The profile studied has a NNW-SSE orientation, perpendicular to the fault (Fig. 1D). The seismic data recorded were processed to obtain the Vp and Vs models whose details are described below.

TABLE 1. Description of the seismic parameters in the study area

Parameter	Description
Seismic source	Accelerated weight-drop (200kg)
Source interval	6m
Source impacts	1
Total Number Shot records	433
Transect Length	2496m
Receiver interval	2m
Geophone Natural Frequency	10Hz
Channels Spread	216
Spread length	430-436m
Recording Time	4s
Sample rate	1ms
File format	SEGY

Seismic data acquisition

The seismic data acquisition consisted of a 240-channel system built up by connecting 10 GEODE recording units with 24 channels each, kindly provided by GIPP-GFZ (Potsdam, Germany). The seismic source used was a 200kg accelerated weight-drop provided by the Instituto Técnico Superior of the University of Lisbon (Lisbon, Portugal). The sample rate was 1ms and the total recording time was 4s. The data were recorded using conventional single vertical component exploration geophones with a natural frequency of 10Hz (Table 1).

The acquisition was carried out by rolling along the recording spread (cable). Once the source was located at the spread's center, the recording spread was moved just before the current source location and the process started again, following a leapfrog scheme. The source was fired every 6m moving along the spread until the source position reached, approximately, half of the spread. The geophone spacing was 2m, resulting in a maximum offset of nearly 500m. The total length of the profile is approximately 2496m and a total of 433 shots were recorded (Fig. 2).

P-wave Travel Time Tomography

P-wave travel time tomography is currently a well-established and broadly used inversion scheme to resolve V_p velocity structure. The reader can find comprehensive reviews of the methodology (Aki and Richards, 1980; Nolet, 1993; Thurber and Atre, 1993). Common approaches use the first arrival travel times and search for the most plausible velocity model that can reproduce the observables by minimizing the time difference between the estimated travel times. Theoretical travel times are thus calculated by using a ray tracing forward modelling scheme. In our study, the first arrivals were handpicked from the shot records (Fig. 3A). A total of 84373 travel time picks from the 93528 available traces were picked, representing 90.2% of the total data available (Fig. 3).

To determine the subsurface velocity distribution from the first arrivals picked travel-times, we used the Delta-T-v inversion method (Rohdewald, 2011). This technique is based on the Common Mid-Point (CMP)-refraction concept (Gebrande and Miller, 1985), that considers the CMP-travel times can be seen as a function of the independent variables CMPx coordinates and the CMP-constant offsets (Fig. 3A). In that sense, two partial differentiations deliver the reciprocal CMP-apparent velocity. In principle, this technique is similar to a forward and reverse-shot analysis with the advantage that extrapolations to the shot points are not necessary, but local layer thicknesses $H(X)$, are found at each CMP. The refractor is obtained as an envelope of circles with a radius around the CMPs at the surface.

The CMP scheme assumes a layered media characterized by a velocity step function (with positive or negative V_p increments) and each layer features a constant velocity gradient (Rohdewald, 2011). It starts with determining the velocity at the base of a layer from CMP travel times curves and then it inverts numerically the velocity at the top of the gradient layer. This approach known as “seismic stripping” can be understood as to physically lower the source and receiver for each ray to the top of the layer below. The algorithm is able to model the diffraction of seismic rays at the top of constrained low-velocity layers. It automatically identifies precise time delays on CMP curves transforming these delays into velocity-depth anomalies. A 1-D velocity-depth function is constrained beneath each CMP. All 1-D velocity-depth functions are integrated through a gridding scheme building up a final 1.5D velocity model. A simple and smooth 1D velocity model is needed to initialize the process. This is obtained by laterally extending a simple 1D layered model along the profile.

Figure 3C shows the first-arrivals times in CMP scheme, in this way effects of dipping layers are averaged and minimized. The travel-times are smoothed by stacking CMP-sorted travel-time curves over a 40 adjacent CMP's. Subsequently, each curve is “Delta-t-v inverted”. For the V_p final model (Fig. 4),

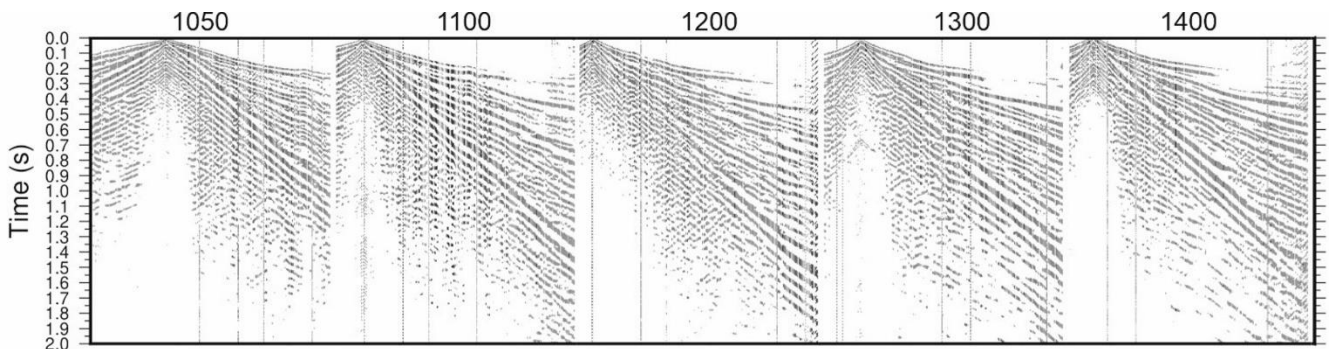


FIGURE 2. Example of seismic shot records acquired along the profile. The shot gathers displayed are raw shots, the seismic traces have been normalized by the maximum amplitude for display purposes.

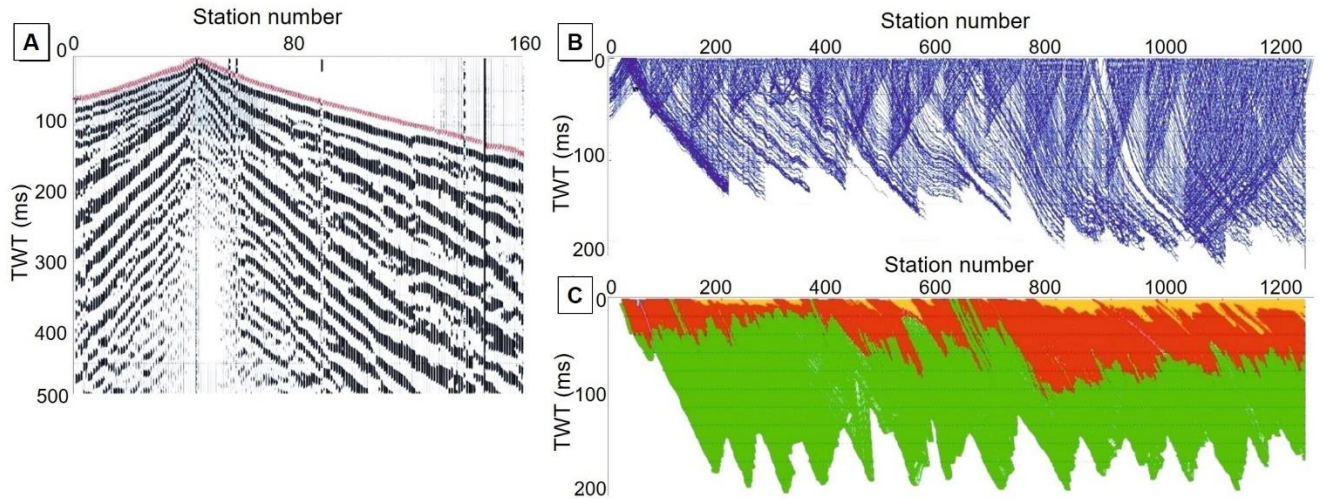


FIGURE 3. Basic inputs to resolve V_p subsurface distribution. A) example of the first-arrival time picked in the shot viewer (red crosses). B) space-time graphs of all picked first-arrivals. C) The first-arrival time picks as a function of the independent variables CMPx (station) and the CMP constant offset; curves are presented with a velocity reduction of 5000m/s.

a Root Mean Square (RMS) error was of 9.09ms, resulting in a normalized RMS error of 3.1% (RMS error, divided by maximum pick time of all traces modelled). The relative misfit function was estimated to reach 41.35ms (squared error summed over all traces modelled, divided by the modelled trace count). The maximum absolute error is 120.43ms for trace 81 in shot 42. Thus, these quantitative indicators suggest that this V_p final model shows a relatively high degree of reliability. However, because of the method used assumes 1.5D geometry we cannot rule out the effects of the real 3D contributions to the final velocity anomaly model.

Surface-wave analysis

Surface waves have a lower velocity than body waves and usually present strong energy in reflection seismic

records, commonly known as ground roll. While the high amplitude surface waves constitute a serious problem in conventional P-wave seismic reflection processing, where they need to be attenuated or even muted out, in the pursued surface wave analysis they constitute valuable data. The depth sampled by a particular frequency component of surface waves is proportional to its wavelength. This characteristic makes the surface wave velocity frequency-dependent, *i.e.* dispersive. The dispersion diagram reveals the surface wave field in terms of frequency and phase velocity. This representation can be inverted to constrain the S-wave velocity (V_s) distribution as a function of depth, allowing to detect effectively V_s anomalies at shallow depths (between 1.5 and 100m) (Lai and Rix, 1999; Lai *et al.*, 2002, 2005; Rix and Lai, 2005; Xia *et al.*, 2000). When this is applied to multichannel data, it is known as

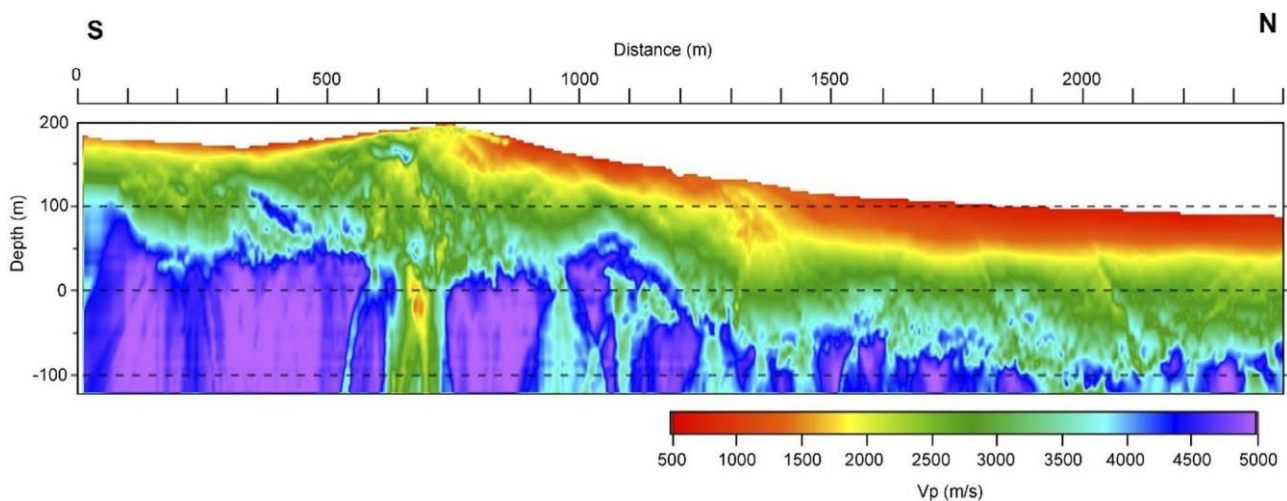


FIGURE 4. V_p model obtained using the 1.5D V_p Delta-t-v method.

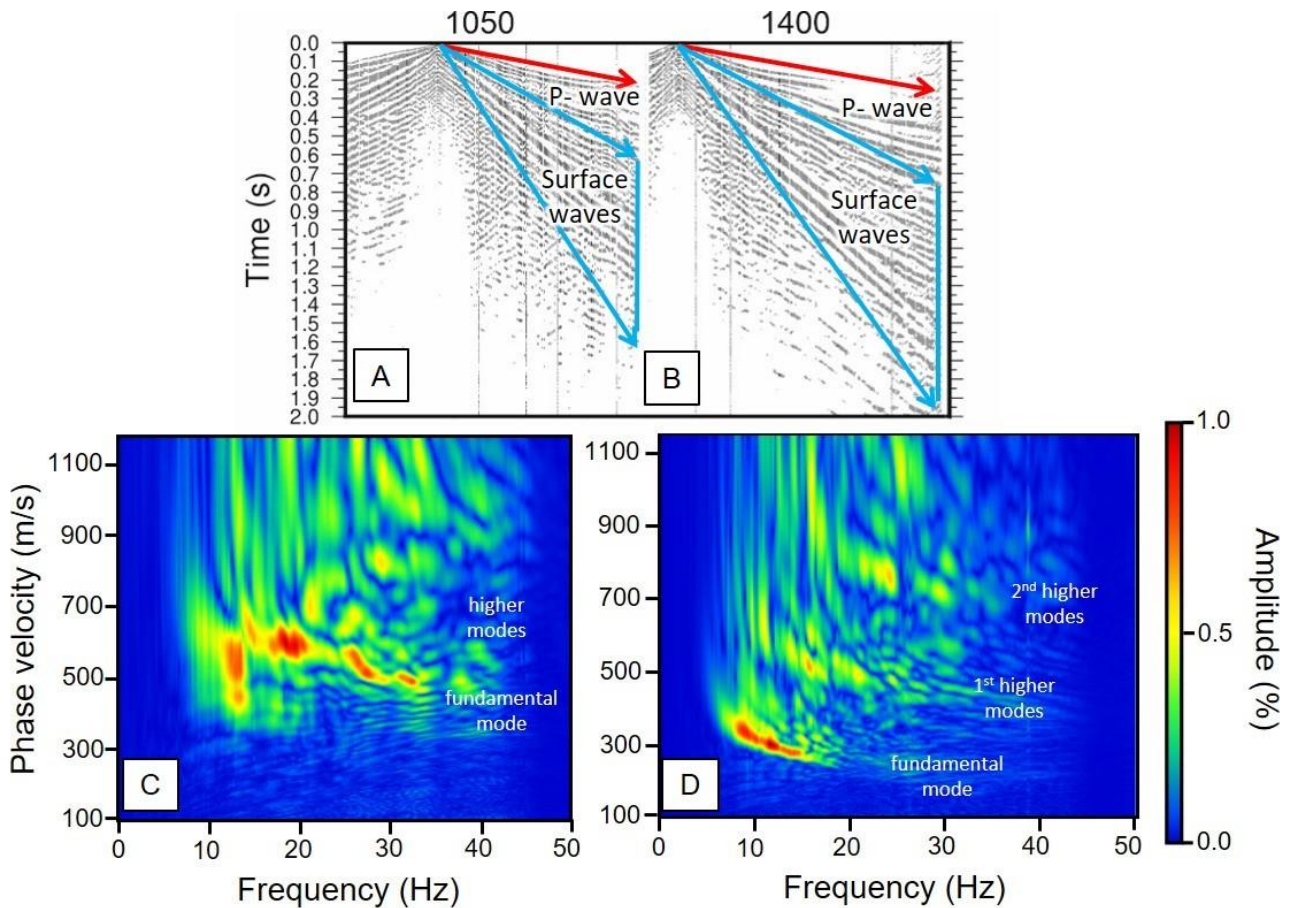


FIGURE 5. A, B) Example of the seismic shot records; for display purposes, traces have been normalized to the maximum amplitude. The dispersive surface waves are indicated by the blue triangular area. C, D) dispersion diagrams for the shot gathers in a and b, respectively. The color scale reveals the contribution of the different frequencies at the different phase velocity. The different dispersion modes are labeled in each diagram.

Multichannel Analysis of Surface Waves (MASW). This methodology was introduced in the late 1990's and early 2000's (Park *et al.*, 1999; Xia *et al.*, 1999, 2000, 2002) and it is able to resolve 1D and 2D Vs models of the shallow subsurface. The conventional approach to address the shear-wave analysis comprises two main steps (Foti *et al.*, 2018). The first step is to determine the experimental dispersion curve; the second is to determine the parameters that define the layered model, *i.e.* the S-wave velocities and densities of each layer. To resolve the inversion problem, the model parameters are defined accordingly (Lai and Rix, 1999; Lai *et al.*, 2002, 2005; Mari, 1984; Xia *et al.*, 2000).

The seismic data presented here features a high amplitude cone of dispersive surface waves, which is very prominent in the shot records (Fig. 5). The surface waves appear within a triangular area with the vertex of the triangle located at zero offset. The frequency content in this region is mostly distributed between 5-50Hz, with the higher amplitudes being within the 10-45Hz frequency band. The observer notes were used to incorporate the acquisition geometry that is the source and receiver UTM coordinates.

This information was used to obtain offset an azimuth for each trace in all shot records. Then, to obtain the dispersion characteristics of the surface waves, we used the frequency/slowness (ray-parameter: f, p) derived from intercept time and ray parameter (τ - p slant-stacks in frequency domain) in different shot gathers (Fig. 5C, D). As a result, we obtained the dispersion diagrams (Fig. 5C, D). The f - V_{ph} (frequency-phase velocity) picking was supervised by the operator, and only the fundamental model was considered.

The second step allows for more alternative procedures as it focuses on the inversion strategy. Although, in general, the inversion strategy is based on the minimization of the misfit between the observations and synthetic simulations (Menke, 1984; Snieder and Trampert, 1999; Tarantola and Vallette, 1982), the evaluation of this function can be achieved in different forms (Socco *et al.*, 2010). The inversion problem is most commonly solved by linear approximation that uses a 1D forward modeling scheme and retrieve a 1D S-wave velocity depth function for each dispersion diagram (obtained from each shot record). The general assumption is that the subsurface is constituted

by a number of layers with constant physical properties for each layer. The resulting velocity-depth function, and/or subsurface physical model can be considered to be represented by a series of “ n ” layers with shear wave velocities ($V_{s1}, V_{s2}, \dots, V_{sn}$), densities ($\rho_1, \rho_2, \dots, \rho_n$) and thicknesses ($t_1, t_2, \dots, t_n$). Through inversion theory (Constable, 1987; Menke, 1984; Parker, 1994; Tarantola and Valette, 1982) the scheme aims to constrain a model (unknown) that is able to reproduce the observables as closely as possible. The inversion is nonlinear and thus an iterative approach is devised, guided by constrained optimization algorithms. The difficulties of such schemes are widely discussed in inversion contributions (Constable, 1987; Menke, 1984; Parker, 1994) and are mostly due to the non-linearities of the problem and/or the non-uniqueness character of its solution. In order to avoid such issues, we considered a strategy that aims to favor the simplest (*i.e.* the smoothest model) that is able to most closely reproduce the measured data. This approach is known as Occam’s Inversion. The mathematical details on the differences between the approaches can be found in Haney and Qu (2010).

The Occam’s Inversion approach was used here to address the site characterization of the fault in the study area. This algorithm has been first described and used extensively by the electromagnetic and magnetotelluric subsurface geophysical characterization community (Constable, 1987; Key, 2009; Werthmüller, 2017). In this approach the subsurface is over-parametrized by using a large number of relatively thin layers (Constable *et al.*, 1987; de Groot-Hedlin and Constable, 1990). The strategy of the algorithm aims to find the smoothest velocity-depth model subject to the constraint of a specified misfit between measured and theoretically computed data, taking into account the uncertainties associated with the data measurements. It is an iterative inversion scheme that requires a starting model, which is consisted of the density, V_p , V_s , and layer thickness (Haney and Qu, 2010; Press *et al.*, 1992; Xia *et al.*, 1999). In our case, the starting model displayed a constant V_s of 500m/s and a density of 2.0g/cm³. This constant velocity model features over 20 layers (all with identical physical properties), with a thickness of 0.5m. The input data consists of frequency and phase velocity picks and error estimates.

The output consists of velocity and standard deviation estimates as a function of depth. The standard deviation is understood as the estimated variability of the inverted velocity. The inverted velocity profiles reach depths down to 250m, and the resolution power decreases with depth, as indicated by the systematic increase of the standard deviation. Therefore, velocity estimates are considered resolved when their standard deviation is below 15%. On average, this assumption limited the resulting models down

to a depth of 150m below the surface. The analysis and inversion were applied to individual shot gathers, and thus 433 analyses and their corresponding 1D velocity-depth functions were obtained. The analyzed shot records feature 6m spacing, and thus the 1-D velocity-depth functions are also assumed to be determined every 6m. Considering that the highest amplitude contributions to the signal are within the frequency band of 10-45Hz, the velocity estimates are assumed have averages over 25-35m length.

The inversion result should not depend on the a priori established information of the starting layered model (n , the number of layers; and their physical properties and geometry). The specific characteristics of the input model (physical properties and layer thickness) are not essential in order to minimize the misfit. Thus, to test this point (the dependence of the result with the starting model), three different starting models were used in which the layer thickness, the velocity, and the maximum depth of the model were changed (depending on the lowest frequency of the data). This was done in a way that allowed to statistically sample the model space and maximize the possibilities that the results do not correspond to a local minimum. In all inversions, a maximum smoothness and regularity in the solution are imposed. This scheme avoids resulting models that are too complex. The output consists of a smooth model and its standard deviation for each shot record. The starting models have included depth down to 400m and layer thicknesses that have ranged from 0.5 to tens of meters. Thus, the preferred starting model consisted of 600 layers, 0.5m thick layers which reached a depth down to 250m.

Once the corresponding 1D velocity-depth functions were obtained for each shot record, they were pasted together to build up a 2D velocity depth model (Fig. 6A). A spatial smoothing operator was applied to the 2D velocity model, in order to spatially balance small-scale sharp anomalies (Haney and Qu, 2010; Key, 2009; Werthmüller, 2017). This operation can be justified by considering that the inverted model is an average estimate over 25-35m wavelength combining the frequency of the seismic signal and the offset contributions. Furthermore, each velocity-depth function is the smoothest model that can reproduce the observations (dispersion diagrams) within a 10-12% standard deviation. A direct comparison between the composite velocity model and the smooth version is displayed in Figure 6B.

RESULTS

The P-wave velocity model

The resulting V_p -depth model (Fig. 4) provides an image of the first 250m of the subsurface, allowing us to characterize the Unidad Roja (alluvial fans sediments),

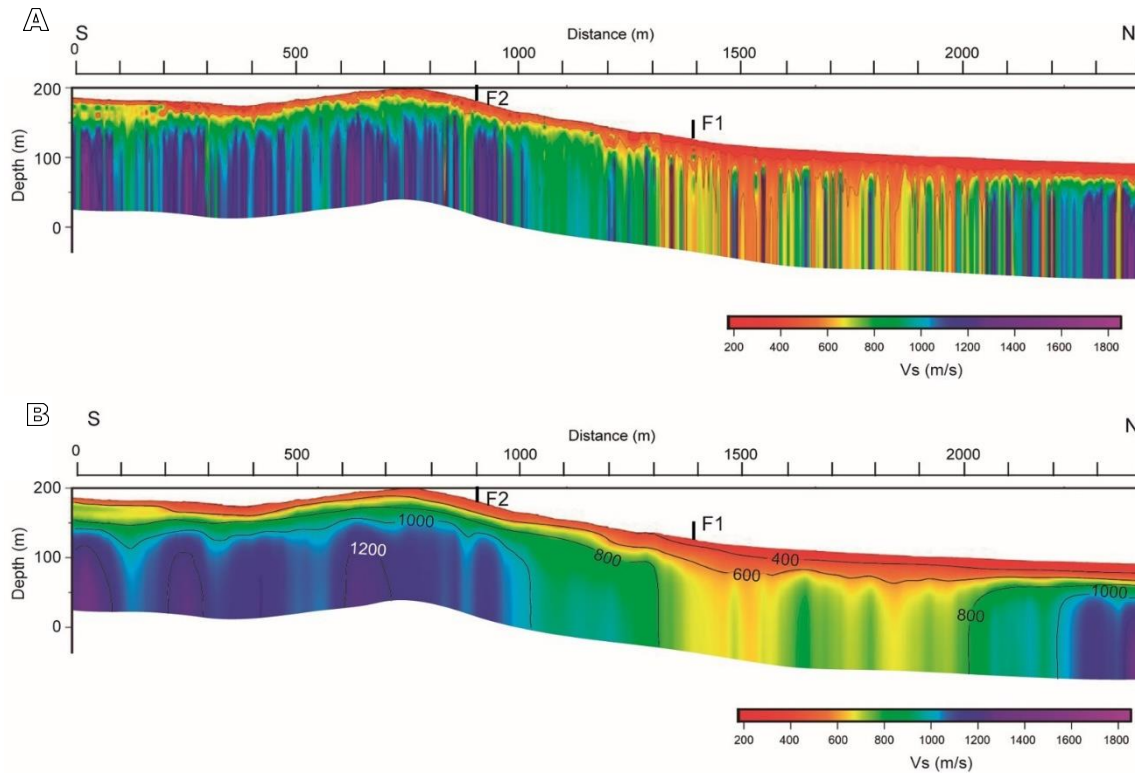


FIGURE 6. Vs model derived from the surface-wave analysis. A) Vs-depth model considering each profile as they were resolved by the inversion form in each of the shot records. B) Vs-depth model once it has been smoothed by considering 35m smoothing operator (see text for explanation). Thin black lines correspond to iso-velocity contours and the numbers indicate their value. The plot has a vertical to horizontal relation of 2:1. Black vertical lines in (A) and (B) indicate the position of fault strands F1 and F2 on the surface (Fig. 1D).

the weathered Messinian marlstones and the rest of Messinian and Tortonian rocks located underneath. Low Vp (<1500m/s) are modeled in the shallower part of the profile as a zone that increases slightly in thickness towards the north, into the Guadalentín Depression. Underneath this low velocity zone, intermediate Vp (1800-3500m/s) shows a variable lateral thickness implying changes in the Messinian rocks most probably due to the effect of the faults affecting the area. A Vp contrast of 3500-4500m/s is identified at 80-90m below sea level along the northern part of the profile and at 40-50m above sea level in the southern part. This Vp contrast has allowed us to interpret the position of the Messinian/Tortonian boundary. In general, Vp values of carbonate rocks (upper Miocene units) range from 3500-4500m/s, which is in the carbonate rock velocity interval in the range of around 3000-6000m/s (Anselmetti and Eberli, 1993; Eberli *et al.*, 2003).

The S-wave velocity model

The resulted Vs model is shown in Figure 6B. This profile provides reliable information of the ~150m depth and reveals a low Vs (200m/s) layer subparallel to the surface, which can be correlated with the critical zone

(Befus *et al.*, 2011; Handoyo *et al.*, 2022). This shallow layer is approximately 15m thick in the southern part of the profile and reaches a maximum thickness of 30-35m at a distance ca. 1400-1500m. Following the description for site characterization of the National Earthquake Hazard Reduction Program (NEHRP, Brown (1981), Table 2), the shallower levels of the profile (Vs ranging from 200 to 500m/s), would be consistent with moderately weathered to weathered sedimentary rocks domains (Types V and IV in Table 2), correlated with the upper Miocene to Holocene sediments cropping out along the profile (Fig. 1D). In addition, this layer thickens towards the north of the northern branch of the Algezares-Casas Nuevas Fault, where the topography is lower corresponding to the sedimentary infill of the Guadalentín Depression.

Under this layer, Vs are significantly higher with abrupt lateral changes. The Vs model derived in this analysis vary from 200m/s (near the surface) to about 1800m/s at depth and presents lateral changes with areas of relatively low-velocity values 200-750m/s, moderate-velocity 750-1300m/s, and high-velocity over 1500m/s. Towards the southern part of the profile, high Vs are located starting at approximately 50m below the surface with their value

TABLE 2. Description and classification of rock domains used in the interpretation. This table aims to integrate the different degrees of weathering and the NEHRP site classification table (NEHRP: National Earthquake Hazard reduction program (Odum *et al.*, 2007; Sun *et al.*, 2015)). The latter is included in the last two columns.

Rock Type	Vs Velocity (m/s)	Detailed description of rock domains integrating degree of weathering and their Site Classification.	NEHRP Site classification and description	
			Vs (m/s)	Type
VII		Unstable soil water unsaturated, mud and undocumented artificial fill; residual soil. All rock material is converted to soil. The mass structure and material fabric are destroyed.		Special soils
VI	< 180	Soft Soil, Completely weathered rock domain, granular sediments mud-sands gravels silts, and mud (Holocene, late Quaternary). All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	< 180	Soft Soil
V	180-360	Stiff soil, highly weathered rock, more than half of the rock material is decomposed and/or disintegrated to soil. Granular Sediments (Mid-late Pleistocene).	180-360	Stiff Soil
IV	360-760	Dense soil/ Soft Rocks Poorly cemented coarse-grained to fine-grain sedimentary rock to dense early to mid-Pleistocene or older granular sediment. Moderately weathered rock. Less than half of the rock material is decomposed and/or disintegrated to soil.	360-760	Dens Soil Soft rock
III	760-1000	Slightly weathered rock domain and relatively hard/fresh rock. Well cemented and lithified coarse-grained sedimentary or low-grade metamorphic rocks. Slightly weathered rock discoloration indicates weathering of rock materials and discontinuity surfaces.	760-1500	Rock
II	1000-1500	Slightly weathered rock domain and relatively hard/fresh rock; slightly weathered intrusive igneous and high-grade crystalline metamorphic bedrock with very limited weathering.		
I	> 1500	Hard Rock Includes un-weathered intrusive igneous rock. Well cemented/lithified. Fresh rock No visible sign of rock material weathering.	> 1500	Hard Rock

decreasing towards the southern branch of the Algezares-Casas Nuevas Fault at a distance ca. 900m (F2 in Fig. 6B). The area of Vs between 900-1200m/s, can be correlated to a slightly altered and fractured area, and/or to a minor degree of relatively unconsolidated rock (Type IV in Table 2). This could indicate an unconsolidated domain most probably a fractured zone associated to the Algezares-Casas Nuevas Fault. This Vs zone is laterally interrupted by a relatively broad slow domain (~800m/s) representing a relatively sharp decrease coinciding with the outcrops of the Guadalentín Depression and limiting with the northern branch of the Algezares-Casas Nuevas Fault (F1) at a distance ca. 1400m. Towards the northern end of the profile, at approximately distance ca. 2000m, velocities increase again, reaching the velocity >1000m/s, from a depth down to 50m. These velocities are above 1000m/s and most probably are indicative of harder rock or more consolidated domains in the subsurface (Adel *et al.*, 2013; Kanli *et al.*, 2006; Olona *et al.*, 2010).

DISCUSSION

Contribution of Vp and Vs modelling to shallow subsurface characterization

The presence of fractures and/or faults greatly influence the physical properties of the shallow subsurface and,

often, the effects of these changes in physical properties are observable by means of seismic methods. Fracturing involves a decrease in rigidity (bulk and shear modulus) of the faulted area and surrounding materials. In addition, the presence of groundwater (fluid content) can further reduce the value of Vp and Vs (Catchings *et al.*, 2014, 2020). As an implication, the velocity values of Vp and Vs around the fault plane decrease with respect to the surrounding rock mass. Previous studies including empirical methods using laboratory data (Wang *et al.*, 1978), seismic velocity from borehole geophysics (Boness and Zoback, 2004), controlled source seismic reflection (Alcalde *et al.*, 2013; Catching *et al.*, 2014, 2020; Martí *et al.*, 2002, 2006a, 2008), and earthquake data (Eberhart-Phillips and Michael, 1998; Thurber and Atre, 1993) reported a significant decrease in seismic velocity (Vp and Vs) within the fault zone, which in can reach up to 50%. In the subsurface, Vs is strongly influenced by the shear modulus and Vp is strongly influenced by the bulk modulus.

Fracturing and weathering reduce shear wave velocity and control surface wave dispersion (Miller *et al.*, 2000; Xia *et al.*, 1999). Therefore, the velocity and dispersion characteristics of surface waves (MASW method) are used to determine the variation of shear wave velocities with depth (Foti *et al.*, 2018; Park *et al.*, 1999). The MASW technique assumes that the subsurface is a laterally homogeneous layered earth media, in which the average

velocity can be assigned to the middle of the receiver spread (Foti *et al.*, 2018; Socco *et al.*, 2010). The MASW method (acquisition, computation and analysis) allows us to investigate shallow subsurface structures in detail, particularly structural features characterized by lateral changes in the seismic velocities. The sensitivity of depth penetration is influenced by several parameters: i) the natural frequency of the observed seismic signal; ii) the array setup (geometry) used for collecting data; iii) the instrument frequency-bandwidth and iv) the velocity sediment/rock of the site (Foti *et al.*, 2018; Park and Carnevale, 2010). Therefore, MASW can be used to characterize lateral shear wave velocity changes in the shallow subsurface.

Following the conventional MASW analysis, in this study we employed surface wave dispersion curves (a total of 416) derived from multiple shot gathers to infer 1D and 2D Vs-depth models. The signal frequencies ranged from 5-10Hz to 45-50Hz (Fig. 5C, D). These frequencies were shown to be sensitive to geological discontinuities at depth, with high frequencies placing constraints on the shallow layers and low frequencies providing information of deeper levels. In addition, the shallowest depth of investigation (Z_{min}) is resolvable between $\lambda_{min}/3 < Z_{min} < \lambda_{min}/2$, where $\lambda_{min} \sim 2dx$ (dx is the receiver spacing). Meanwhile, the maximum wavelength λ_{max} corresponds to the array length L , where the value is about $\lambda_{max} \approx L$ (Park and Carnevale, 2010). In practice, the expected maximum depth of examination is about from $\lambda_{max}/3 < Z_{max} < \lambda_{max}/2$ (Foti *et al.*, 2018). According to the acquisition geometry of this profile (Table 1), the best resolution is obtained between $\sim 2m$ and $\sim 150m$ (Fig. 6).

The use of high-resolution Vs and Vp models, together with the surface geology information (trench and geological mapping) can help to increase confidence in the determination of the shallow subsurface structures and the characterization of the critical zone (Handoyo *et al.*, 2022; Ivanov *et al.*, 2006; Miller *et al.*, 2000; Rempe and Dietrich, 2014). This work provides a successful example of combination of a P-wave tomography and MASW to unravel the shallow subsurface structure in an active tectonic setting. The Vp model provides a reliable image down to ca. 250m and allows to identify stratigraphic contacts and faults. The Vs model complements the Vp model by showing areas of damage due to intense tectonization, and subsequent more intense fluid circulation. The combined interpretation of the resulting Vs and Vp models allows us to characterize: i) the thickness of the critical zone, Unidad Roja and alluvial fans; ii) the depth of the contact between the Messinian and the Tortonian rocks; iii) the geometry of the Algezares-Casas Nuevas Fault; iv) blind faults and a damaged area associated to the Algezares-Casas Nuevas Faults and v) a new slip rate estimation for the Algezares-Casas Nuevas Fault. These outcomes are discussed in the following sections.

Thickness of the critical zone, Unidad Roja and alluvial fans

The high-resolution Vp model presented here has allowed us to accurately locate the contact of the shallower geological units: i) the Unidad Roja and the Quaternary alluvial fan deposits towards the north of F2 and ii) a meteorized layer of marlstone towards the south of F2 (Fig. 7A). The maximum thickness of the Unidad Roja and the Quaternary deposits is identified under the Guadalentín Depression, where they show a thickness of ca. 50m. Complementary, the Vs model provides information about the thickness of the critical zone and a damage area (Fig. 7B) (Handoyo *et al.*, 2022).

Towards the south, F2 shows two strands that most probably merge at depth and form a monocline in the hanging wall, as observed in the surface. The Unidad Roja outcrops until ca. 650m along the study profile (Fig. 1) and south of this position. The Messinian rocks show also a very low seismic velocity in the first tens of meters, which may correspond to a weathered layer of marlstone. There, the critical zone is formed by different layers of disaggregated materials and weathered bedrock, the so-called regolith, and jointed/fresh bedrock (Befus *et al.*, 2011; Rempe and Dietrich, 2014) that in our profiles is as a layer subparallel to the surface in the Vs model.

Taking a closer look at this layer in the elevated area towards the south of F2, a small thickness difference at both sides of the point of highest elevation at a distance of ca. 600-1000m corresponds to the monocline on the hanging wall of F2. It is relevant to point out that this small thickness difference between the northern facing and south facing slopes is also detected in the un-smoothed velocity model (Fig. 6A). This thin layer of slow Vp and Vs to the south of F2 could be considered as a relatively thin blanket of heterogeneous deposits, loose and unconsolidated rocks (Type IV and V in Table 2) (Francisca and Bogado, 2019) and where fluids flow recharging and/or discharging the aquifers. This domain would be consistent with the regolith. Thicker regolith on north facing slopes compared with south facing slopes of the monocline has been reported from geophysical studies (Befus *et al.*, 2011; Rempe and Dietrich, 2014; St Clair *et al.*, 2015). In these areas, the interaction of tectonic stresses with topography influences the thickness of the regolith. In the study area, the thickness of this shallow layer is strongly influenced by the overall oblique reverse deformation that characterizes the surroundings of the Algezares-Casas Nuevas Fault.

Depth of the Messinian-Tortonian contact

The stratigraphic series in this profile is, from deepest to shallowest: i) Tortonian: limestone sandstones, marls,

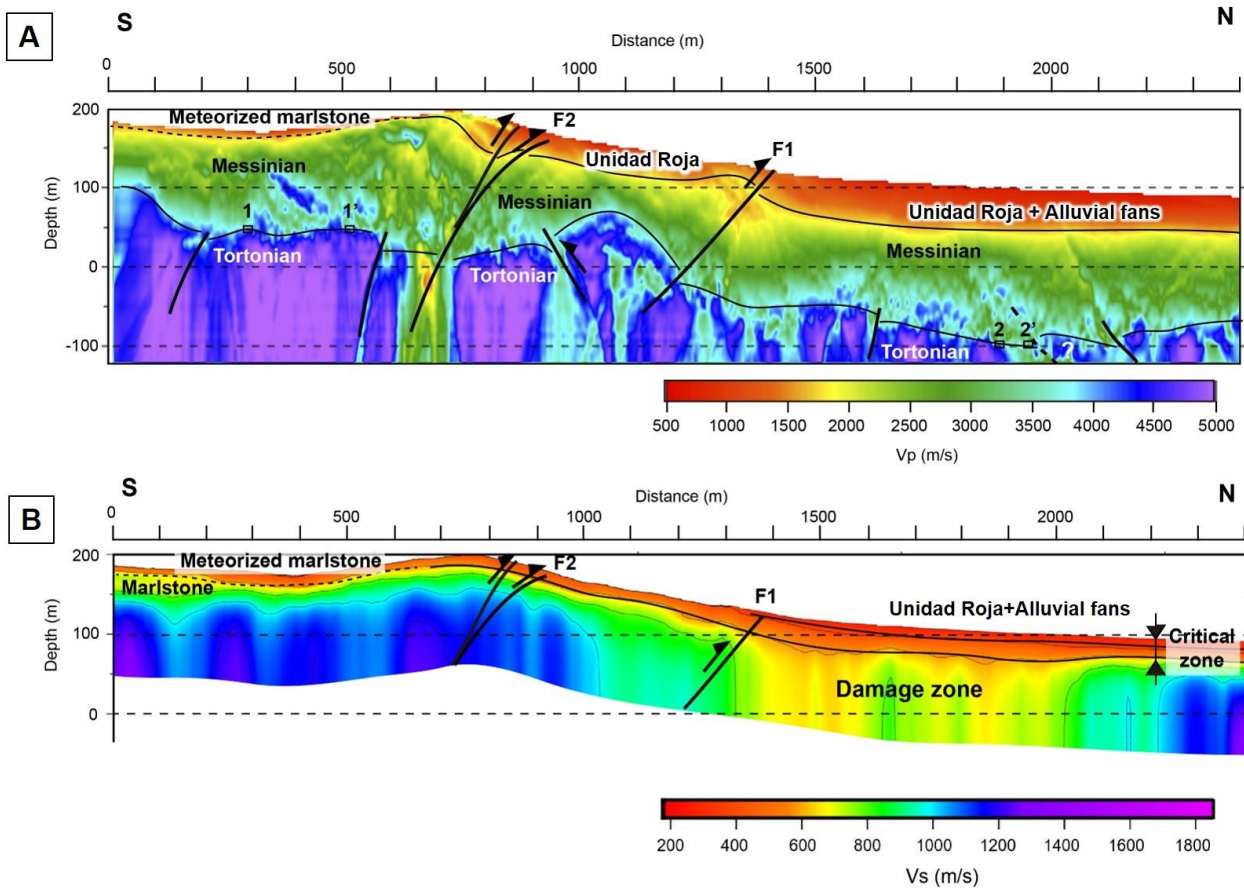


FIGURE 7. Geological interpretation of the: A) Vp model. Numbers 1, 1' and 2, 2' represent the points used to calculate the vertical slip rate of the Algezares-Casas Nuevas fault (see text for details) and B) Vs model.

and gypsum; ii) Messinian: conglomerates, sandstone and limestone, and marls in contact with Unidad Roja; iii) Plio-middle Pleistocene-Unidad Roja: cemented conglomerates; iv) Quaternary: conglomerates less consolidated, the more recent generations are unconsolidated sediments (gravels, sands and silts).

The contact Tortonian-Messinian is marked by conglomerates and sandstones in the Messinian base and marls in the Tortonian top. We have interpreted that the contact between the Messinian and the Tortonian rocks is located along the Vp contrast of 3500m/s to 4500m/s. This model reveals a thickness for the Messinian rocks range from ~50m between F1 and F2, to 170m immediately south of F2 (Fig. 7A). The thickness of the Messinian inferred from geological mapping in the vicinity of the profile varies between 40m and 100m. This is coherent with the contrasts observed in the velocity models and the thickness obtained. This boundary is located at 80-90m below sea level in the southern part of the profile (number 1 in Fig. 7A) and at 172m depth to the northern end of the profile (number 2 in Fig. 7A). The lateral variation on the depth of this boundary

may suggest the existence of blind faults that may disrupt it and would contribute to increase the damage reducing the Vs values under the Guadalentín Depression (Fig. 7B).

Geometry of the Algezares-Casas Nuevas Fault

The high-resolution seismic velocity models presented here allow us to identify the structure of the strands of the Algezares-Casas Nuevas Fault (Fig. 7). F1 and F2 correspond to relatively low-angle N-vergent faults which would merge at depth (as proposed by Martín-Banda *et al.*, 2016), although the depth resolution of our models is not enough to image that geometry. In addition, we have interpreted two blind faults to the south of F2 and one blind fault between F1 and F2 based on the displacement of the Messinian-Tortonian contact at distances ca. 200m, 600m, and 950m at the depth between 50m to 0m (in Fig. 7A).

In Figure 6B, F1 is positioned at a distance of ca. 1400m and F2 at a distance of ca. 900m base on their outcrops. From Figure 7A and B, based on the Vp and Vs models, F1 is depicted following the outcrops data

that dipping to the south until a depth of ca. 80-100m with the velocity V_p 1700-2000m/s and V_s 600-800m/s. Furthermore, in the deeper zone (Messinian-Tortonian contact), the F1 fault is not characterized by V_s model. The F1 fault is interpreted by velocity V_p 3000-3500m/s at the depth of ca. 0m to -20m. Meanwhile, near the surface (Unidad Roja-Messinian contact), the F2 fault is characterized by velocities of V_p 1500-2000m/s and V_s 600-800m/s at a depth of 150m to the surface. Then, at a depth of about 0-30m (Messinian-Tortonian contact), the fault F2 is represented by the velocity V_p 3000-3500m/s. In addition, the fault propagation anticline in the Unidad Roja associated to F1 could be extended deeper connecting with an area where a south vergent thrust is interpreted to uplift the Tortonian rocks between F1 and F2.

Indeed, F1 and F2 are relatively low-angle oblique reverse faults that displace the Unidad Roja and the middle-upper Pleistocene alluvial fans and, therefore, with activity during the Quaternary (Martín-Banda *et al.*, 2016). Between F1 and F2, the rocks of the Unidad Roja form an anticline in the hanging wall of F1. In turn, the southern strand, F2, may be formed by several branches which may merge at ca. 30-40m above sea level, carrying in its hanging wall a monocline structure. This monocline could be linked to a blind fault on the Messinian-Tortonian contact at a distance of ca. 600m and at ca. 0m above sea level may have led to a change in the bedrock height levels, with implications for tectonic stress in the sub-vertical direction to the surface.

Blind faults and damage zone under the Guadalentín Depression

Fracture systems can play a key role in weathering processes, as they represent pathways for fluid flow, facilitating the interactions of corrosive fluids with minerals and allowing the drainage of neutral (chemically balanced) brines. There is an almost linear relationship between the density of cracks and the decrease in the elastic modulus and thus with the V_s . Theoretical studies by Budiansky and O'Connell (1980) and references therein, derive seismic velocity in terms of aspect ratios (thickness/length) considering the fractures as cracks geometrically described as oblate ellipsoids, and the elastic properties of the matrix and fluids. The larger the concentration of fractures, the higher the degree of weathering interaction and, therefore, the lower the V_s . The differences in the values of velocity anomalies between the interpreted fractures (F1 and F2), probably reflect the effect of the different degree of fracturing and, therefore, of weathering.

Under the Guadalentín Depression, the V_p model reveals up to two south-vergent blind thrusts that disrupt the Messinian/Tortonian contact. We interpret these structures as strands of the Alhama de Murcia Fault which crops out

further north, in the northern border of the Guadalentín Depression. Indeed, several branches of the Alhama de Murcia Fault have been interpreted based on gravimetric data (Amores *et al.*, 2002, 2021), which characterized a highly tectonized area under the Guadalentín Depression. The gravimetric data (density models) obtained in this study was carried out with a trajectory stretching from Carrascoy Fault to AMF through the Guadalentín Depression in the middle. The interpretation of the geological structure from the density model shows that there are several faults under the Guadalentín Depression, which are probably the branches of the AMF. Based on the low-velocity under the Guadalentín Depression, we interpret this area as a damage zone (Fig. 7B). Therefore, under the Guadalentín Depression, a high density of blind faults would have intensely tectonized the area, allowing fluids to infiltrate lowering the V_s values (700-900m/s). The low velocities would then be related to fracturing and local weathering that would reduce the shear modulus value and associated to weathering. In the same area of the V_p profile, not a significant decrease of the V_p is identified (~ 3000 m/s), suggesting that the damage area is caused by high fluid circulation that affected mainly the V_s . In addition to the outcropping strands of the Algezares-Casas Nuevas Fault, we interpret the presence of a blind south vergent thrust that plays most probably in F1 and that forms an antiform on its hanging wall at the distances ca. 1650m and 2100m (Fig. 7A). Furthermore, two blind faults are mapped at 50m and 100m below sea level, slightly displacing at the Messinian-Tortonian contact/displacement. In the V_s model (Fig. 7B), the Algezares-Casas Nuevas Fault (area between F1 and F2) is interpreted as a contrast area where a reduction of the V_s may indicate a more tectonized or altered zone.

Slip rate estimations

Based on the above, the shallow subsurface structures in the southern Guadalentín Depression and northernmost edge of the Carrascoy Range have been unraveled. Here, we provide an image of the first 250m depth of the area allowing us to identify the structure at depth of outcropping faults, the locus of several blind thrusts, the thickness variations in the Upper Miocene units, as well as areas of intense fluid circulation.

In addition, the identification of the Messinian/Tortonian and Unidad Roja/Messinian contacts in both blocks of the Algezares-Casas Nuevas Fault enables us to estimate an apparent vertical slip rate knowing that the onset of the formation of the fault was around 209.1 ± 6.2 ka (average value from Martín-Banda *et al.*, 2016). Specifically, the Messinian/Tortonian contact apparent vertical displacement from one block to the other is quoted in 135 ± 15 m (points 1 and 1' respect to points 2 and 2' in Fig. 7A). This displacement is consistent and practically identical, 140 ± 20 m, taking as reference the Unidad Roja/

Messinian contact respect to the base of the outcrop of the Messinian on the upthrown block located southwards of the seismic profile. Considering these displacements accumulated since the onset of fault activity in 209.1ka, we calculate a vertical slip rate of $0.66 \pm 0.06 \text{ m/ky}$ considering the error propagation from the displacement measurements as well as for the time. This value is slightly higher than the $0.34 \pm 0.02 \text{ m/ky}$ (Ferrater *et al.*, 2017) and $0.37 \pm 0.08 \text{ m/ky}$ estimated by Martín-Banda *et al.* (2016), and lower than the $1.3 \pm 0.2 \text{ m/ky}$, calculated based on GPS data in the Alhama de Murcia Fault (Echeverría *et al.*, 2013). However, our estimated value is very similar to the $0.64 \pm 0.4 \text{ m/ky}$ established for the net slip rate along the NE Segment of the Carrascoy Fault for the last 220ky (similar period) (Martín-Banda *et al.*, 2021). This difference in the slip rate calculated is not surprising, as previous values were calculated in a different part of the same fault, where the Algezares-Casas Nuevas Fault features one major strand, and according to the restitution of the top of the Unidad Roja based on data from trenches (Martín-Banda *et al.*, 2016). Our slip rate value is estimated from the apparent displacement of the Messinian-Tortonian contact in an area where the Algezares-Casas Nuevas Fault depicts a complex geometry of fault strands that may have played a role displacing the Messinian-Tortonian contact.

On the basis of the above, we can conclude that Vp tomography provides a reliable image of the subsurface and that combined with MASW allow to image the geometry of the shallow structure (Anderson, 2015; Anderson *et al.*, 2011, 2013; Parsekian *et al.*, 2015; St Clair *et al.*, 2015), where tectonized or altered areas represent preferential paths for fluids. Both methodologies combined are useful for the characterization of the critical zone that comprises the regolith and the jointed/fresh bedrock. To further study the stress interaction between strike-slip and oblique reverse tectonics, the kinematics of the blind faults that could represent a higher risk as previously thought, and the lateral continuations of the active structures, a multidisciplinary coincident 3D geophysical data is required, including resistivity and Lidar, among others (Anderson *et al.*, 2013; Leone *et al.*, 2020). Further work will provide new Vp and Vs models along other faults of the EBSZ providing a larger picture of the shallow subsurface structure of this strike-slip system. The combination of methods presented in this article represent valuable high-resolution resources for the characterization of the shallow subsurface in tectonically active regions, improving seismic hazard models and reducing the potential risk caused by active structure zones in the other areas.

CONCLUSIONS

The P-wave velocity model and Multichannel Analysis of Surface Waves (MASW) have been applied to unravel the

shallow subsurface structure of one of the most active fault systems in the Iberian Peninsula, the Eastern Betics Shear Zone (EBSZ). Specifically, we have sampled the Algezares-Casas Nuevas Fault, a relatively low-angle oblique reverse fault located in a left-lateral strike-slip fault system between the Carrascoy range and the southern border of the Guadalentín Depression. In this study, we provide new P- and S-wave velocity (Vp and Vs respectively)-depth models, reaching a maximum depth of 250m. P-wave velocity was determined from the Delta-t-v method and S-wave velocities are estimated from the surface waves recorded within the control source shot records of conventional seismic reflection data (MASW).

The interpretation of these models has allowed us to identify significant features of the subsurface: i) the critical zone and thickness of the Pliocene-Holocene sedimentary cover; ii) the depth of the contact between the Messinian and the Tortonian rocks; iii) the geometry of the strands of the Algezares-Casas Nuevas Fault and iv) the location of blind faults and a damaged area associated to Algezares-Casas Nuevas Faults and possibly to the Alhama de Murcia Fault. Additionally, it has allowed us to calculate a new vertical slip rate estimate for the Algezares-Casas Nuevas Fault. The critical zone along the study profile consists of a layer of low Vp and Vs parallel to the surface and slightly thicker to the north of the profile, the Guadalentín Depression. This layer is mainly formed by sediments of the Pliocene-Middle Pleistocene (Unidad Roja) and the Plio-Quaternary alluvial sediments in the Guadalentín Depression and towards the southern part, it corresponds to weathered Messinian marlstone. The depth of the Messinian/Tortonian boundary is identified along the Vp profile as a contrast of 3500 to 4500m/s. The apparent disruption of the interpreted surface allowed us to interpret at least two antithetic faults. The Algezares-Casas Nuevas Fault is interpreted to be formed mainly by two major N-verging strands (F1 and F2), although other related blind faults can also be interpreted. It is noteworthy the presence of a blind S-verging thrust between F1 and F2 that may form an antiform in its hanging wall. Under the Guadalentín Depression, two S-verging blind faults are interpreted disrupting the Messinian/Tortonian boundary. Those structures could be related to strands of the Alhama de Murcia Fault, which crops out in the northern border of the Guadalentín Depression, about 5km from these S-verging structures. Specifically, the southernmost part of the Guadalentín Depression features very low Vs under the critical zone. We interpret this as a damage zone resulted from an intense fluid circulation in the aquifers. Finally, we propose a slip rate of $0.66 \pm 0.06 \text{ m/ky}$ (in the last $209.1 \pm 6.2 \text{ ky}$) for the Algezares-Casas Nuevas Fault based on the depth of both the Unidad Roja/Messinian and Messinian/Tortonian contacts south of F2 and to the north of this damage zone identified in the Vs model. This work represents a successfully combined MASW and

P-wave tomography study to unravel the shallow subsurface structure of a tectonically active zone.

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CHAPTER 6
**Geophysical Imaging of the Critical Zone along the Eastern Betic Shear Zone
(EBSZ), SE Iberian Peninsula**

“I have seen the further it is by standing on the shoulders of giants.”
— Isaac Newton

Article

Geophysical Imaging of the Critical Zone along the Eastern Betic Shear Zone (EBSZ), SE Iberian Peninsula

Handoyo Handoyo^{1,2,3}, Juan Alcalde^{1*}, Irene DeFelipe⁴, Imma Palomeras⁴, Raquel Martín-Banda⁵, Julián García-Mayordomo⁵, David Martí⁶, José J. Martínez-Díaz⁷, Juan Miguel Insua-Arévalo⁷, Teresa Teixidó⁸, Ignacio Marzán⁵ and Ramon Carbonell¹

¹ Geosciences Barcelona (GE03BCN, CSIC), 08028 Barcelona, Spain; handoyo.geoph@tg.itera.ac.id (H.H.); ramon.carbonell@csic.es (R.C.)

² Teknik Geofisika, Institut Teknologi Sumatera, South Lampung 35365, Indonesia

³ Facultat de Ciències de la Terra, Universitat de Barcelona, 08028 Barcelona, Spain

⁴ Departamento de Geología, Universidad de Salamanca, 37008 Salamanca, Spain; idefelipe@usal.es (I.D.); imma@usal.es (I.P.)

⁵ Instituto Geológico y Minero de España (IGME-CSIC), 28003 Madrid, Spain; r.martin@igme.es (R.M.-B.); julian.garcia@igme.es (J.G.-M.); imarzan@csic.es (I.M.)

⁶ Lithica SCCL, Santa Coloma de Farners, 17430 Girona, Spain; dmarti@lithica.net

⁷ Department of Geodynamics, Stratigraphy and Paleontology, Universidad Complutense de Madrid, 28040 Madrid, Spain; jmdiaz@geo.ucm.es (J.J.M.-D.); insuarev@geo.ucm.es (J.M.I.-A.)

⁸ Instituto Andaluz de Geofísica y Prevención de Desastres Sísmicos, Universidad de Granada, 52005 Granada, Spain; tteixido@ugr.es

* Correspondence: jalcalde@geo3bcn.csic.es



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Abstract: The critical zone (CZ) represents the most-shallow subsurface, where the bio-, hydro-, and geospheres interact with anthropogenic activity. To characterize the thickness and lateral variations of the CZ, here we focus on the Eastern Betic Shear Zone (EBSZ), one of the most tectonically active regions in the Iberian Peninsula. Within the EBSZ, the Guadalentín Depression is a highly populated area with intensive agricultural activity, where the characterization of the CZ would provide valuable assets for land use management and seismic hazard assessments. To achieve this, we have conducted an interdisciplinary geophysical study along the eastern border of the Guadalentín Depression to characterize the CZ and the architecture of the shallow subsurface. The datasets used include Electrical Resistivity Tomography (ERT), first-arrival travel time seismic tomography, and multichannel analysis of surface waves (MASW). The geophysical datasets combined help to constrain the high-resolution structure of the subsurface and image active fault systems along four transects. The resulting geophysical models have allowed us to interpret the first ~150 m of the subsurface and has revealed: (i) the variable thickness of the CZ; (ii) the CZ relationship between the fault zone and topographic slope; and (iii) the differences in CZ thickness associated with the geological units. Our results provide a method for studying the shallow subsurface of active faults, complementing previous geological models based on paleo-seismological trenches, and can be used to improve the CZ assessment of tectonically active regions.

Keywords: critical zone (CZ); ERT; fault; MASW; tomography

Introduction

The critical zone (CZ) defines the outermost surface layer of the earth, where the atmosphere, meteoric water, biota, soil, and bedrock interact [1,2]. The CZ extends from the unaltered rock to the top of the canopy of plant vegetation on the ground surface [3] (Figure 1). The CZ hosts life and the energy and resources to sustain it, and it is the subject of an increasing body of research. Researchers and government entities have highlighted the role of the CZ for our society in different economic and environmental aspects, and the need for a correct and robust characterization of this important layer [4–7].

The CZ, from top to bottom, comprises: the soil (that includes the organic horizon, the surface horizon A, and the subsoil horizon B), regolith, fractured bedrock, and fresh bedrock (Figure 1). The CZ also comprises the near-surface aquifers. The formation of the CZ is a combination of two important processes, namely: (i) soil layer erosion, which can remove weathered materials from the topsoil surface (surface topography), and (ii) rock weathering processes, which occur mechanically and chemically and that can breakdown rock layers, separating the underlying altered bedrock and fresh bedrock [8–10]. The thickness of the CZ can range from 0.7 m to 223.5 m, being thicker in midlatitudes [11].

The production of regolith from fractured bedrock can increase the surface area and distribution of weatherable minerals and expose them to increased water intrusion from the surface. The thickness of the regolith controls groundwater storage and flow paths in highly complex system landscapes such as mountainous landscapes and is highly correlated with topographic slopes or gradients [12,13]. All the activity that occurs in the CZ will greatly determine the level of mass and energy exchange between the biosphere system, the regolith layer, and the earth's atmosphere [14–17]. Thus, understanding the geometry, area, and physical properties of the CZ is crucial for the sustainability of the surrounding ecosystem.

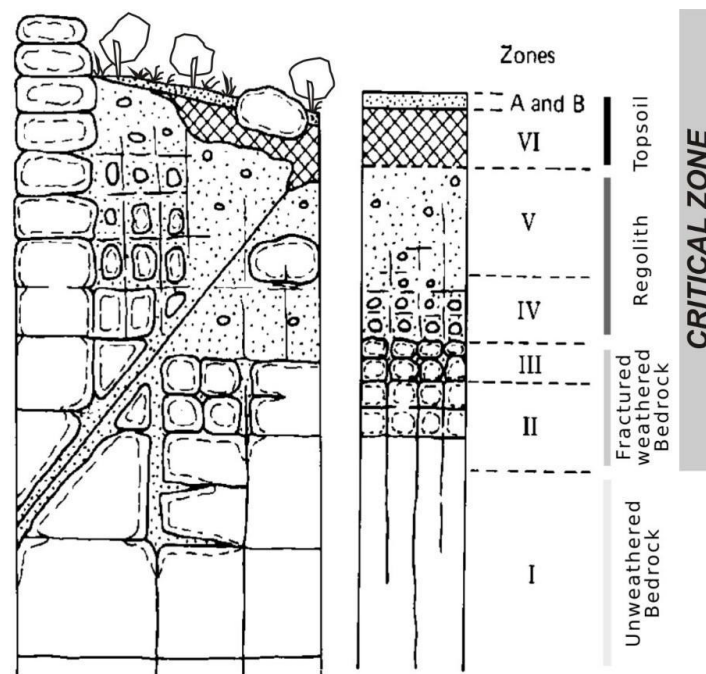


Figure 1. Simplified model of the critical zone regarding the weathering profile developed on rock masses (modified from [18–20]). Zones I to VI defined by the degree of weathering [18].

Geophysical methods have been used in the past to try to characterize and constrain the CZ, its formation, and the processes that occur within it, e.g., the analysis of deep rock weathering and groundwater storage potential; studies on transport processes, reactivation, and kinetics processes; imbalances of chemical processes in the water surface boundary plane, and tectonic fracture activity [21–24]. These processes are interrelated and influence each other in the formation of the CZ. Some works that focused on the study of the CZ used seismic wave velocities and electrical resistivity to demonstrate the influence of topographic stress and fault activity on bedrock fault distribution [25,26]. Specifically, in the EBSZ, the structure of the CZ was first characterized by P-wave tomography and MASW across the frontal strands of the Carrascoy fault system, namely the Algezares-Casas Nuevas fault (ACNF) [27]—in review. This study revealed the underground structure, the CZ, and the damage zone related to blind faults buried under the Guadalentín Depression. Nevertheless, the along-strike variations of the structure in the EBSZ and the CZ thickness

and properties could not be estimated, requiring a comprehensive geophysical study along with different areas of this fault system.

In this study, we investigate the geometry of different fault zones and the distribution of the CZ using coincident seismic and electrical surveys in the EBSZ along four profiles (La Torrecilla, La Salud North, La Salud South, and Carrascoy). To characterize the CZ along the EBSZ, we have used indirect geophysical methods, including P-wave tomography, Multichannel Analysis of Surface Waves (MASW), and Electrical Resistivity Tomography (ERT) on the profiles of La Torrecilla and La Salud North. Meanwhile, the P-wave tomography and MASW were applied to the profiles of La Salud South and Carrascoy. The main goals of this investigation are to map the CZ, to characterize fault structure, to map the weathered distributions in the subsurface that are influenced by fault activity and topographic slope, and to study the relationship between geological units and the thickness of the CZ.

Geological Setting

The EBSZ runs across the Internal Zone of the Betic Cordillera, a mountain belt that resulted from the convergence between the Nubian and Eurasian plates since the late Neogene (Figure 2A) [28,29]. The Internal Zone is formed by a stack of tectometamorphic complexes formed of Paleozoic, Mesozoic, and Cenozoic rocks that were exhumed during the Paleogene [30,31]. Subsequently and until the middle Miocene (Serravalian), former thrusts were reactivated as low-angle normal faults under extensional tectonics related to the opening of the South Balearic basin (e.g., [32,33]).

Partly coetaneous with this extension (from the Langhian to the Messinian), an intense magmatic activity took place in this area [34], and Neogene sedimentary basins formed (e.g., Lorca and Fortuna basins) [35]. At the end of the Messinian/beginning of the Pliocene, the tectonic convergence between the Nubian and Eurasian plates under an NNW-SSE regional shortening direction [28,36,37], inverted previous Neogene basins, and the Guadalentín Depression formed in an area that was previously uplifted [35,38,39]. Furthermore, the NNW-SSE regional shortening direction has not changed in the region since the late Miocene [40], as evidenced by GPS data.

The study area is located in the central and northern part of the EBSZ (Figure 2B). There, the Guadalentín Depression is bordered to the north by the Alhama de Murcia fault (AMF) and to the south by the Carrascoy fault system (CAF), NE-SW left-lateral strike-slip faults with a reverse component [41] (Figure 2B). The AMF is divided in four sections from SW to NE according to their geomorphological expressions, seismicity rates and fault zone geometries [42]: (i) Góñar-Lorca, a N40E narrow fault zone that ends in a horsetail to the south; (ii) Lorca-Totana, a section with a N60E trend and ~2 km wide fault zone where Gómez-Novell [43] identifies at least five strands; (iii) Totana-Alhama de Murcia, also with numerous strands, which recovers the N40E trend and loses geomorphological expression (outcrop of fault plane) northeastward; and (iv) Alhama de Murcia-Alcantarilla, where this expression is very diffuse, possibly because the deformation in this sector is transferred to CAF [42]. In turn, the CAF is formed by two overlapping segments [44].

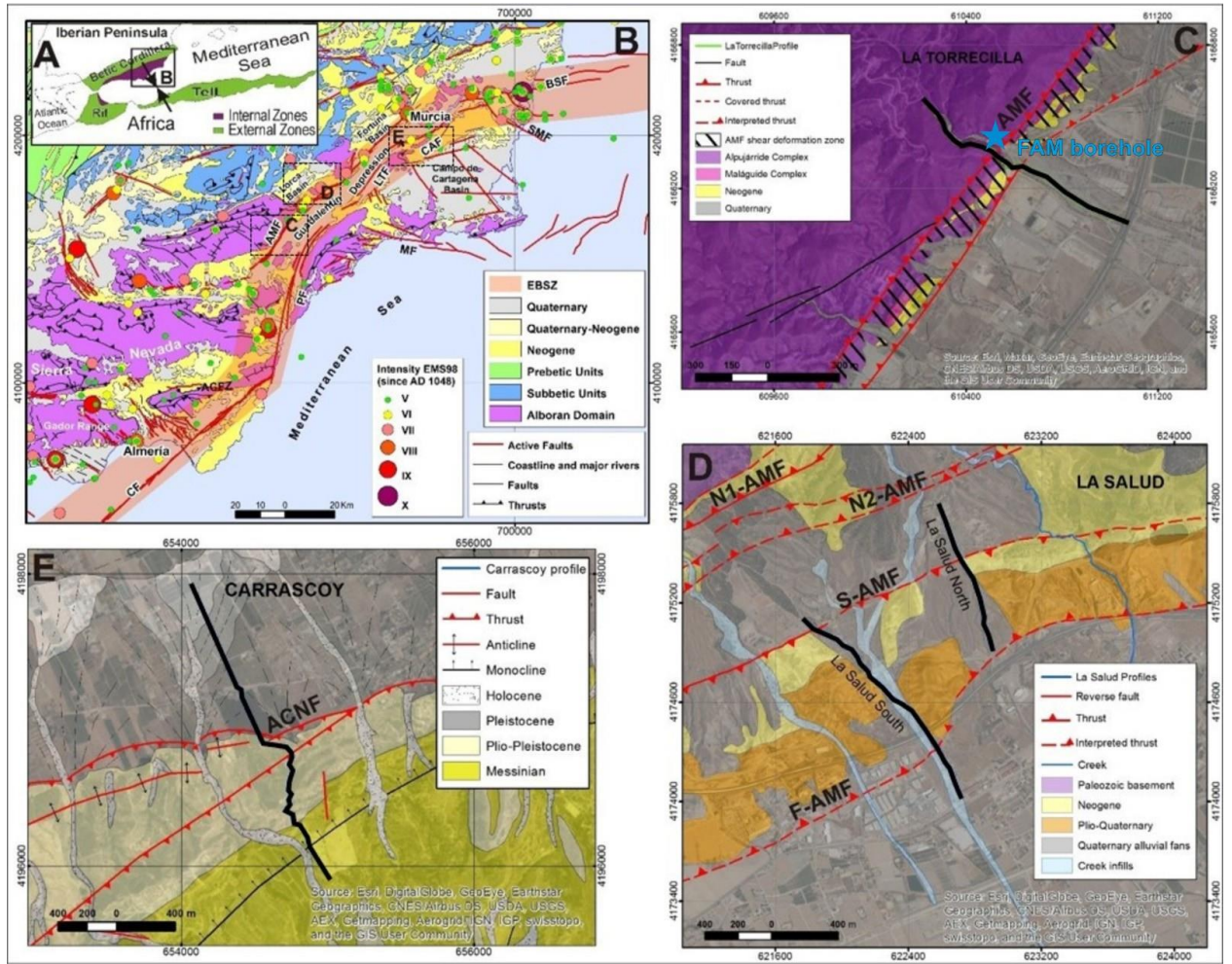


Figure 2. Geological setting of the study area. (A) Geodynamic frame of the study area. Arrows indicate the current approximation direction between Eurasian and Nubian plates. (B) Geological and seismological setting of the Eastern Betic Shear Zone (EBSZ); SMF: San Miguel de Salinas Fault; BSF: Bajo Segura Fault; CAF: Carrascoy Fault; LTF: Los Tollos Fault; AMF: Alhama de Murcia Fault; PF: Palomares Fault; CF: Carboneras Fault; ACFZ: Alpujarrides Corridor Fault Zone; MF: Las Moreras- Escarpe de Mazarrón Fault. Geological mapping was carried out from Continuous Digital Maps at scale of 1:50.000 of the Internal Zones of the Betic Cordillera [45]. Active fault traces are from an updated version of QAFI database [46,47]. Earthquake data correspond to a declustered version of the Spanish national seismic catalog [48]. (C–E) represent the locations of Figure 2C–E. Geological setting of the La Torrecilla profile modified from Martínez-Díaz et al. [49]. The blue star marks the position of the scientific borehole FAM-1. AMF: Alhama de Murcia Fault. (D) Geological setting of the La Salud North and La Salud South profiles modified from Gómez-Novell [43]. N1-AMF, N2-AMF, S-AMF, and F-AMF are the names of the different strands of the AMF in this sector. (E) Geological setting of the Carrascoy profile modified from Martín-Banda et al. [44]. ACNF: Algezares-Casas Nuevas Fault.

The SW segment is represented by: (i) the Carrascoy fault sensu lato, that uplifted the Carrascoy Range, and (ii) the Algezares-Casas Nuevas fault (ACNF), that runs for 23 km from the villages of Algezares to Casas Nuevas [44,50]. This area was studied by MASW and P-wave tomography, revealing the underground structure, damage zone related to blind faults, and allowed us to propose a vertical slip rate for the Algezares-Casas Nuevas fault of 0.66 ± 0.06 m/kyr since 209.1 ± 6.2 ka [27]—submitted.

The La Torrecilla profile is located in the northern sector of the Góñar-Lorca section of the AMF (Figure 2C). A single strand and 100 m wide deformation shear zone separates

the metamorphic rocks from the Quaternary deposits of the Guadalentín Depression (Figure 2C). The AFM in this area was also investigated with the drilling of the 175 m scientific borehole FAM-1 (Figure 3, location in Figure 2). The FAM-1 borehole was drilled to examine the mineralogical and geomechanical behavior of the AFM fault zone, by sampling both fault zone and unaltered deposits [51]. The well-log data acquired included gamma ray (GR), Vp, Vs, and resistivity, and more than 100 m of core samples were recovered.

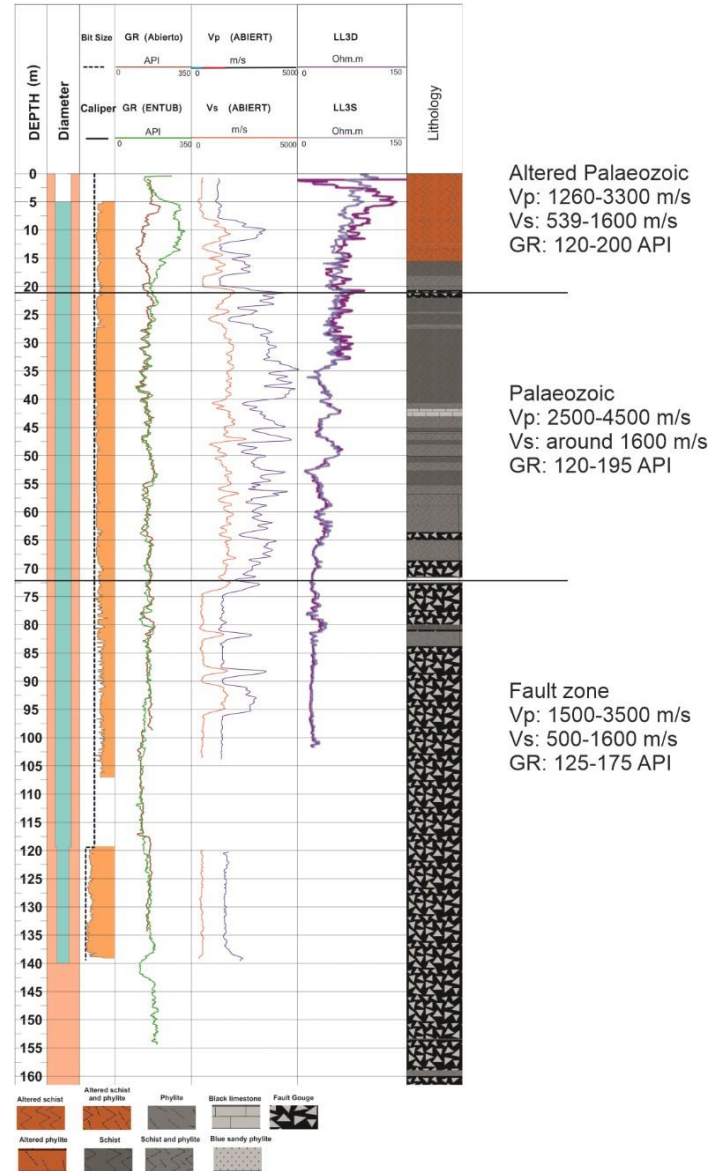


Figure 3. Gamma ray (GR), P-wave velocity (Vp), S-wave velocity (Vs), and resistivity logs recorded in the FAM-1 borehole (location in Figure 2C).

The Góñar-Lorca shear zone shows deformed Upper Miocene materials (marls, sandstones, and conglomerates) and a 20 m wide band of fault gouge that involves Alpujárride and Maláguide Complexes (phyllites, quartzites, and schists). The La Salud South and North profiles are located in the center of the Lorca-Totana section of the AMF (Figure 2D). In this sector, the fault controls Neogene sedimentary rocks from the Guadalentín Depression (mainly marls and gypsums) and Paleozoic rocks from the Alborán Domain (phyllites, quartzites, and schists). The La Salud South profile runs through the two southernmost strands (S-AMF) and the frontal branch (F-AMF) from the four identified in this section (e.g., [43,52–54]). In Figure 2D, the La Salud North profile does not reach the southernmost

strand (F-AMF) but it does in the central strand (S-AMF) [43]. This portion of the S-AMF was also studied by Martí et al. (2020) employing magnetotelluric methods. Finally, the Carrascoy profile is located in the SW Segment of CAF (E; Figure 2B). Specifically, it crosses the fold-and-thrust system that conforms the ACNF on the foreland of the Carrascoy Range (Figure 2E) constituted by Upper Miocene marine sedimentary rocks (marl, biocalcarene, and limestone) and Pliocene-middle Pleistocene continental deposits (conglomerate, gravel, sand, marl, limestone, etc.) (e.g., [44]). The youngest materials are middle Pleistocene to Holocene alluvial deposits that fill the Guadalentín Depression in all studied sectors. They correspond with at least five generations of alluvial fan systems and valley floor deposits, constituting an example of the transition from alluvial to fluvial sedimentary systems [55].

Geophysical Data and Methodology

The geophysical data used in this study consisted of two datasets, namely electrical resistivity data and seismic data. Resistivity data were obtained from the Electrical Resistivity Tomography (ERT) method, while seismic data (Vp and Vs) were obtained from the multi-channel analysis of surface waves (MASW) and P-wave travel time tomography. The resistivity and seismic data used in this study were acquired within the INTER GEO research project, which was funded by the Spanish national research program.

Electrical Resistivity Tomography

The ERT method allows the electrical resistivity properties of rocks beneath the surface to be calculated and is a well-established method in near-surface characterization studies [56–59]. The subsurface resistivity is strongly influenced by a rock's properties, such as porosity, mineral composition, fluid content, and fault structure [60,61]. In this study, the ERT method was only applied in Torrecilla and La Salud North.

The ERT data was acquired with a 12-channel resistivimeter (ABEM Terrameter-RL-12) that involves 80 electrodes deployed at 10 m spacing. The electric spread consists of four lines with 21 electrode connections. For electronic continuity of the entire survey, the first and last electrodes are always overlapped between two lines (21-1 connections). This means that we worked with four cables registering at same time covering 800 m length in total. In order to reach the entire length of the profiles, we used the overlap technique shifting one electric line (21 electrodes) [62]. The apparent resistivities were obtained with the *gradient-plus* electrode protocol, a hybrid electrode configuration that involves a combination of the symmetric Wenner-Schlumberger with the asymmetric dipole-dipole [63,64]. This configuration provides a dense near-surface coverage and allows an investigation target of more than 120 m depth.

During the field acquisition the data quality was controlled by measuring each pseudo-midpoint twice, and for differences of apparent resistivities > 1%, four measures were averaged. The processing workflow used is described in Table 1. To obtain the 2D geoelectric models, we use two commercial software packages, Porosys II (www.iris-instruments.com/, accessed on 22 March 2022) and Resix2Dinv (www.geometrics.com, accessed on 22 March 2022). The first one was used to review the raw data, remove negative values, and define the track geometries. In a second stage, the Resix2Dinv inversion software was run twice: first, with only the most spurious data removed; and second, with a new dataset including data with apparent resistivity differences lower than 25% (an example of this procedure for the La Torrecilla profile is shown in Figure 4). The resulting final models of Torrecilla and La Salud North profiles after 5 and 7 iterations, respectively, had absolute errors of 5.8 and 7.2, respectively.

Table 1. Processing workflow used to obtain the ERT models in La Torrecilla and La SaludNorth profiles.

Software Package	Processing Step	Rationale
Prosys II (Iris Instruments) Resix2Dinv	Step 1	Data point inspection
	Step 2	Negative values removal (filtering)
	Step 3	Insertion of the topography
	Step 4	Adjust the X,Z points along theGPS track
	Step 5	Edition of bad data points
	Step 6	Selection of inversion parameters
	Step 7	Display of model parameterization and selection ofa finer mesh (Figure 4a)
	Step 8	With the new dataset, return to step 6 for a new iteration process(Figure 4b)

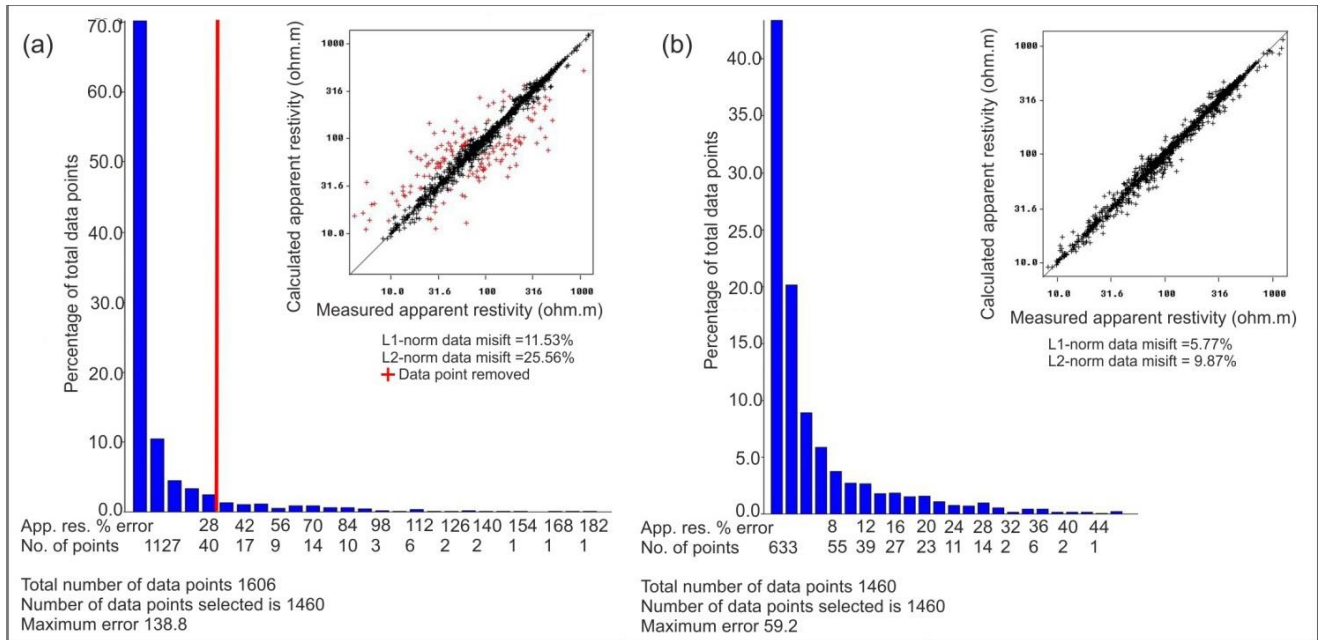


Figure 4. (a) Error distribution after 9 iterations (absolute error = 11.53) between calculated and measured resistivities for the La Torrecilla ERT survey in first inversion. (b) Error distribution after five iterations (absolute error = 5.8) between calculated and measured resistivities in second inversion, once the points that exceeded 25% misfit (red crosses) were removed.

Seismic Data Acquisition

The seismic reflection acquisition experiment included four dense transects across different sections of the fault system. The seismic recording scheme was a 240-channel system made up of 10 GEODE recording units with 24 channels each. The seismic source was a 200 kg accelerated weight-drop provided by the University of Lisbon's Instituto Tecnico Superior (Lisbon, Portugal). The acquisition geometry was designed with a 6 mshot spacing and a 2 m receiver interval. The sample rate was 1 ms, and the total recording time was 4 s. The data was collected using single vertical component exploration geophones with a natural frequency of 5 Hz (Table 2). The seismic data acquired were used in both MASW and P-wave tomography methods described in the next sections.

Table 2. Description of the seismic parameters in the study area.

Seismic Survey Parameter	Description
Seismic source	Accelerated weight-drop (200 kg)
Source interval	6 m
Source impacts	1
	i. La Torrecilla = 1278 m
Transect Length	ii. La Salud North = 960 m
	iii. La Salud South = 1488 m
	iv. Carrascoy = 2496 m
Receiver interval	2 m
Geophone Natural Frequency	5 Hz
Recording Time	4 s
Sample rate	1 ms
File format	SEGY

Multichannel Analysis of Surface Waves

The multichannel analysis of surface waves (MASW) method estimates the S-wave velocity (V_s) of the subsoil from the recorded surface waves. Surface waves have a dispersive nature when propagating through layered media, that is, each frequency has a different penetration depth and thus travels at a different velocity. The dispersion curves (Figure 5) describe the relationship between the phase velocity and the corresponding frequency and can be inverted to predict the V_s distribution as a function of depth in both 1D and 2D [65]. The main process in MASW is the transformation of the recorded surface waves from time (s) and offset (meter) domain (as data is recorded) to the phase velocity (m/s) and frequency (Hz) domain, to form the surface wave dispersion curve [66].

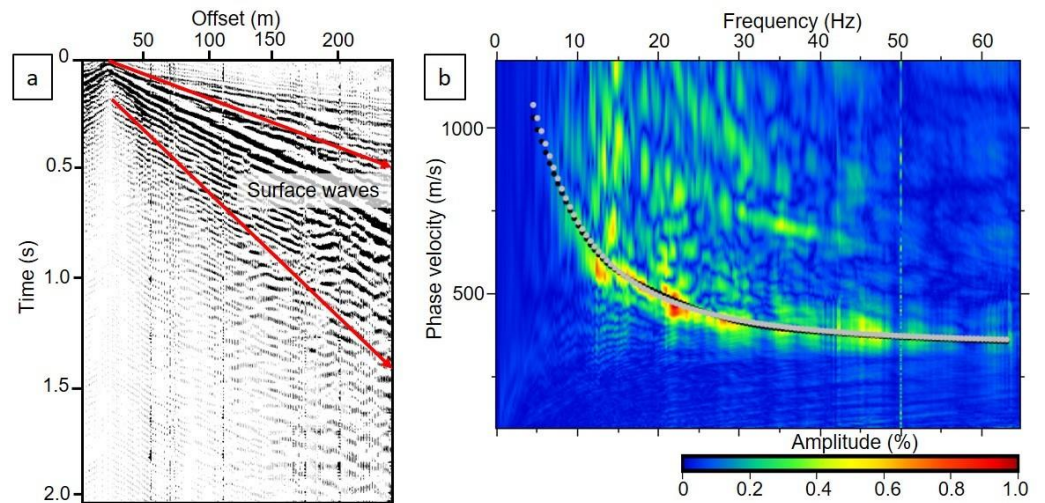


Figure 5. (a) Example seismic shot record with labelled red arrows showing the extent of the surface waves. (b) Corresponding dispersion diagram. The high amplitudes are indicative of the different phases (frequency and phase-velocity). The theoretical and inverted curves are shown as white and black dots, respectively.

In this work, we retrieved the dispersion curves using the wavefield transformation in each shot gather [67]. Then, we inverted each dispersion curve following an Occam's inversion algorithm [66] to get a 1D V_s model at each shot gather position. Finally, we created the pseudo 2D V_s velocity profiles interpolating and merging the 1D V_s models. To average spatially balanced small-scale sharp anomalies, a spatial smoothing operator was applied to the 2D velocity model. This operation can be justified by considering that the inverted model is an approximation of the average at a wavelength of 25–35 m combining the frequency of the seismic signal and the offset contribution. Furthermore, each velocity-

depth function is the smoothest model that can reproduce observations within a standard deviation of 10–12%.

P-Wave Tomography

We used the academic 3D tomographic code Pstomo_eq [68,69] to run the inversion of the first arrival times. The forward modeling part of the algorithm, responsible for the travel time computations and ray tracing in the isotropic model, consists of a first-order finite difference approximation of the Eikonal's equations [70,71]. Once the travel-times to all shots or receivers are calculated, the ray paths are determined by tracing backward from the shot or receiver locations that are perpendicular to the isochrons map [72]. The software has two different schemes implemented to carry out this forward modeling based on Hole and Zelt [73] and Tryggvason and Bergman [71]. The inversion is performed with the conjugate gradient solver LSQR (least square) that iteratively solves the velocity model updates.

For the P-wave tomography study, we semi-automatically picked the seismic first arrivals using the commercial software Globe Claritas (Figure 6). The high quality of the recorded data allowed us to pick up 90% of the travel times, which include all the offset ranges, reaching to maximum offsets of 480 m. This high percentage of successful picked first arrival, even in areas with some anthropogenic activity-related noise, ensures a good lateral and depth resolution for the top 100 m.

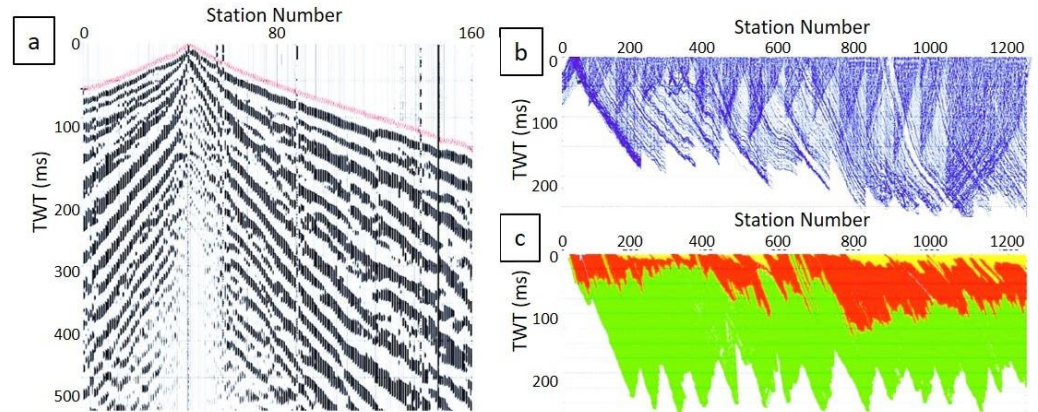


Figure 6. The fundamental inputs for resolving the P-wave velocity subsurface distribution. (a) Example of the first-arrival times picked in the shot viewer (red crosses); (b) the space-timegraphs of all picked first-arrivals; and (c) the first-arrival time is picked as a function of the independent variables CMPx (station) and the CMP constant offset. Ray paths are shown with a velocity reduction of 5000 m/s.

The setup of initial 2D velocity models used in the inversion were based on surface geology and on the well-logging data of the FAM-1 well, located next to the La Torrecilla area (Figure 1) [51]. These starting velocity models assure a good convergence of the tomographic inversion providing an average reduction of the RMS misfit of 80%, providing final RMS travel time residuals ranging from 2–16 ms. The high-resolution seismic data acquired in the area led us to velocity models with final inversion cell sizes of around 2×2 m.

Results

The thickness of the CZ can be obtained by combining multi-geophysical data and mapping the minimum thickness that is matched with all the data [74,75]. In this study, the identification of the CZ from geophysical data includes three parts, namely topsoil, regolith, and weathered bedrock. To determine the distribution of the CZ layer in the different profiles, we have interpreted the zone featuring low-velocities ($V_p < 1200$ m/s and $V_s < 600$ m/s) and high-resistivity ($\rho > 200 \Omega\text{m}$). In the profiles of La Torrecilla and La Salud North, CZ is defined by resistivity $\rho > 200 \Omega\text{m}$, $V_p < 1300$ m/s, and $V_s < 600$ m/s.

While in the profiles of La Salud South and Carrascoy, CZ is defined by $V_p < 1300$ m/s and $V_s < 600$ m/s. Finally, the interpretation of the CZ is the minimum thickness of the CZ constrained by all geophysical data (coincident geophysical data).

La Torrecilla

Figure 7a shows the resistivity model, Figure 7b shows the V_p model, Figure 7c shows the V_s model, and Figure 7d illustrates a combined interpretation of three geophysical data. The resistivity and seismic velocity models obtained from the La Torrecilla profile reveal distinct domains in the shallow subsurface. The CZ is represented by a high resistivity area ($\rho > 200$ m) to the SE of the profile (Figure 7a), which is consistent with the expected high resistivity of Quaternary alluvial fan deposits and fluvial sediment composed of conglomerates, gravels, sands, silts, and clays. Another high resistivity area is identified at surface levels at a distance of 0 to 450 m along with the profile. Underneath the high resistivity area, a medium resistivity area (50–150 Ω m) corresponds to the Paleozoic basement. At distances of 450 to 550 m, there is a ~500 m wide low resistivity ($\rho < 50$ Ω m) that features net and parallel limits. This sector is interpreted as a wide fault zone between two fault planes (Figures 1 and 2) belonging to the AMF shear deformation zone. This shear zone is formed by a 20 m wide band of well-developed fault gouge in Permian-Triassic quartzites and phyllites from the Alpujarride Complex together with sheared Upper Neogene marls, sandstones, and conglomerates.

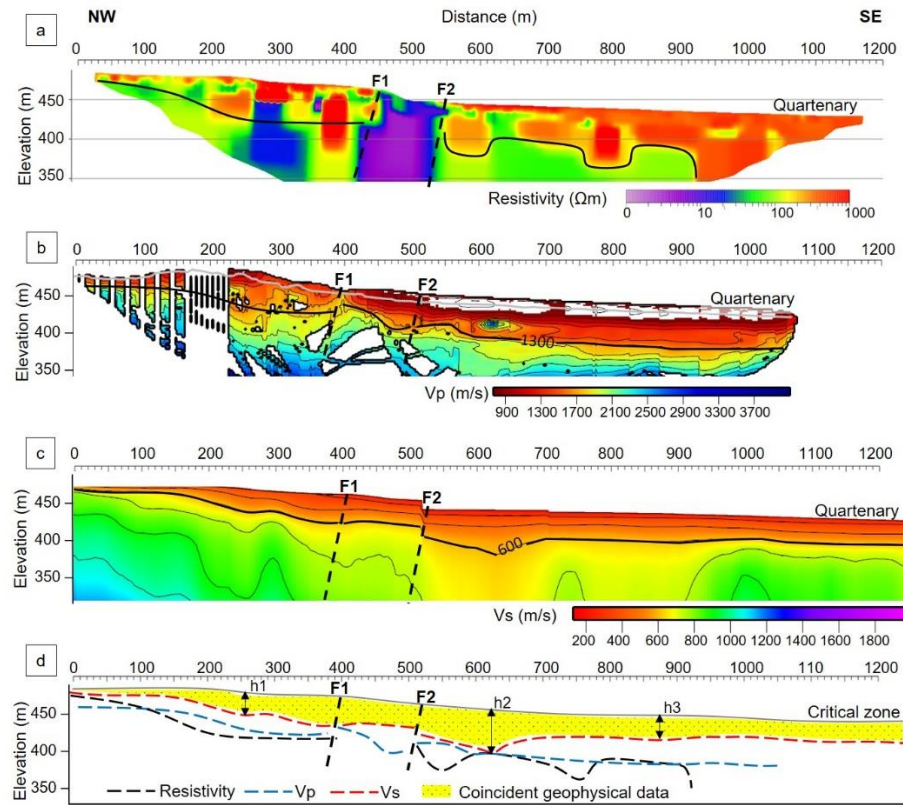


Figure 7. Geophysical imaging of the La Torrecilla with the interpretation proposed and details. Black line indicates the thickness of the CZ. (a) The resistivity profile, (b) the V_p profile from first arrival P-wave tomography, (c) the V_s profile from MASW, and (d) a joint comparison of the CZ inferred from the different geophysical methods. The dot-yellow pattern is shown when the three methods match in their interpretations. The low-velocity anomaly (limited between F1 and F2) corresponds to the AMF shear deformation zone [49]. The variation in thickness of the CZ is indicated by h1, h2, and h3.

Figure 7b,c show the V_p and V_s distributions, respectively. Both models show a low seismic velocity subparallel to and near the surface. The CZ is characterized by a low seismic velocity ($V_p < 1300$ m/s and $V_s < 600$ m/s) with thickness variation in the

NW-SE direction of 30–40 m at a distance of ca. 300 m (h1), which increases by 50–60 m at a distance of ca. 530 m (h2), and thins again to 30–35 m at a distance of ca. 980 m (h3). At the same distance, the CZ interpreted by Vp and Vs (Figure 7b,c) also appears to match the distribution of the high resistivity in Figure 7a ($\rho > 200 \Omega\text{m}$). These low velocities correspond to the Quaternary fluvial sediments, alluvial fan deposits and sedimentary rocks in the southern half of the profile, south of the shear zone. At a distance of ca. 400–500 m, there is a fault zone that is relatively parallel to Figures 1 and 2, which is represented by a discontinuity low-velocity layer. Bedrock layers characterized by values of Vp > 1300 m/s and Vs > 600 m/s were interpreted as more compact and rigid rock formations, i.e., the fresh bedrock that underlies the CZ. These Vp, Vs, and resistivity values are in line with those recorded in the well-logs of the FAM-1 borehole (Figure 3).

La Salud North

The geophysical models for La Salud North profile are depicted in Figure 8. The resistivity profile (Figure 8a) shows striking lateral variations on the resistivity. The CZ is interpreted by high resistivity ($\rho > 200 \Omega\text{m}$) reaching the surface in the NW and SE parts of the line profile. This is consistent with the Quaternary formation's expected high resistivity, which is formed by alluvial gravel and siltstone deposits. The medium resistivity (50–150 Ωm) corresponds to the Tortonian-Messinian formation with marl and interlayered sand and gypsum along the NW-facing profile path at a depth of more than 50 m. A low resistivity $\rho < 50 \Omega\text{m}$ at a distance of ca. 450–900 m is interpreted as the Messinian-Pliocene formation with sandy and marl siltstone and interlayered laminated gypsum and marl. The low resistivity contact is interpreted as a fault zone (defined by the fault planes F1 and F2 in Figure 8) that corresponds to the S-AMF strand. This low resistivity was also clearly identified in the resistivity model obtained by inversion of magnetotelluric data reported by Martí et al. (2020) [48]. The authors interpret this area as an alternation of resistors and conductors (50 $\Omega\text{m}/5000 \Omega\text{m}$) produced by the alternation of shallow levels of very dry colluvial materials cut by vertical faults.

The Vp and Vs profiles (Figure 8b and Figure 8c, respectively) show a low seismic velocity area subparallel to the surface. The CZ is characterized by low seismic velocity (Vp < 1300 m/s and Vs < 600 m/s), which corresponds to the Quaternary formations. On the NW-SE board, the thickness of the CZ varies from 30–40 m at a distance of ca. 100 m (h1), increases by 40–50 m at a distance of ca. 350 m, very close to the fault zone F1 and F2 (h2), and re-thins by 30–40 m at a distance of ca. 750 m (h3). The bedrock is characterized by a velocity layer of Vp > 1300 m/s and Vs > 600 m/s. In turn, the fault zones F1 and F2 are indicated by the low-velocity contrast of Vp which is well correlated with the ERT results. Meanwhile, another fault is predicted from the geophysical interpretation that is located at a distance of ca. 120 m.

La Salud South

The La Salud South profile was only sampled with seismic methods, and so only the Vp and Vs models are available (Figure 9). A low seismic velocity anomaly (Vs < 600 m/s and Vp < 1200 m/s) runs parallel to the surface, which may indicate the presence of the CZ. The CZ thickens towards the SE direction, which in h1 is about 30–40 m at a distance of ca. 200 m, in h2 is 40–50 m at a distance of ca. 430 m, and in h3 is 50–55 m at a distance of ca. 1200 m close to fault F3 (fault F3 is mapped at a distance of ca. 1200 m). The bedrock is characterized by a velocity layer of Vp > 1300 m/s and Vs > 600 m/s. The low-velocity contrast is interpreted as a fault zone at a distance between ca. 310 m and 600 m defined by the fault planes F1 and F2 that correspond to the S-AMF strand.

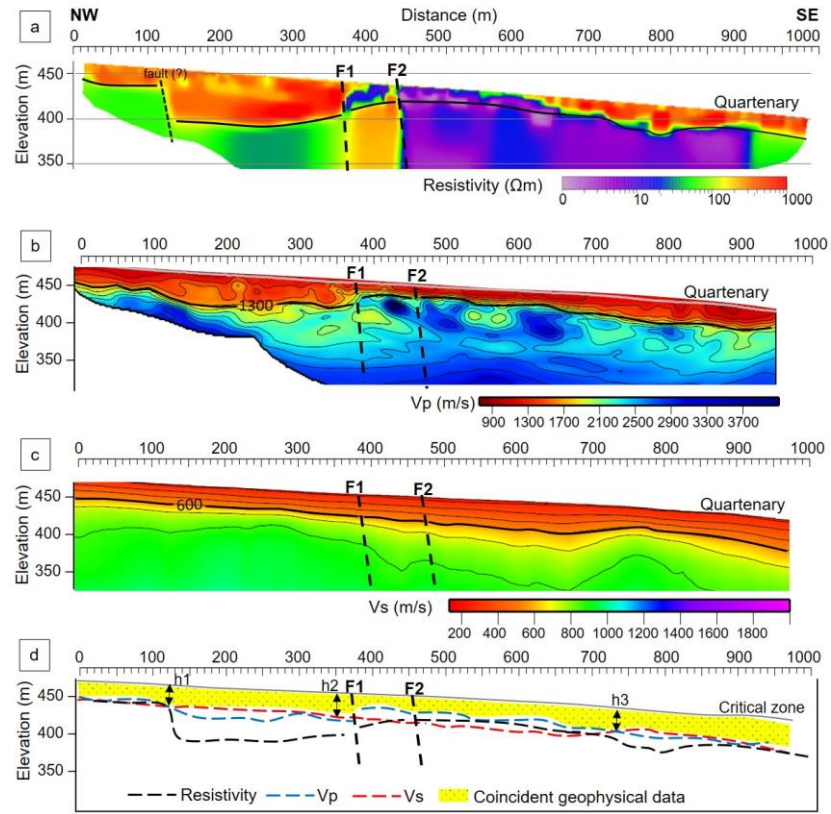


Figure 8. Geophysical imaging of La Salud North site along ~1000 m NW-SE with the interpretation proposed. (a) The resistivity profile, (b) the Vp model, (c) the Vs model from MASW, and (d) a joint comparison of the interpreted CZ. The resistivity contact marked by Figures 1 and 2 corresponds to the AMF shear zone in this sector.

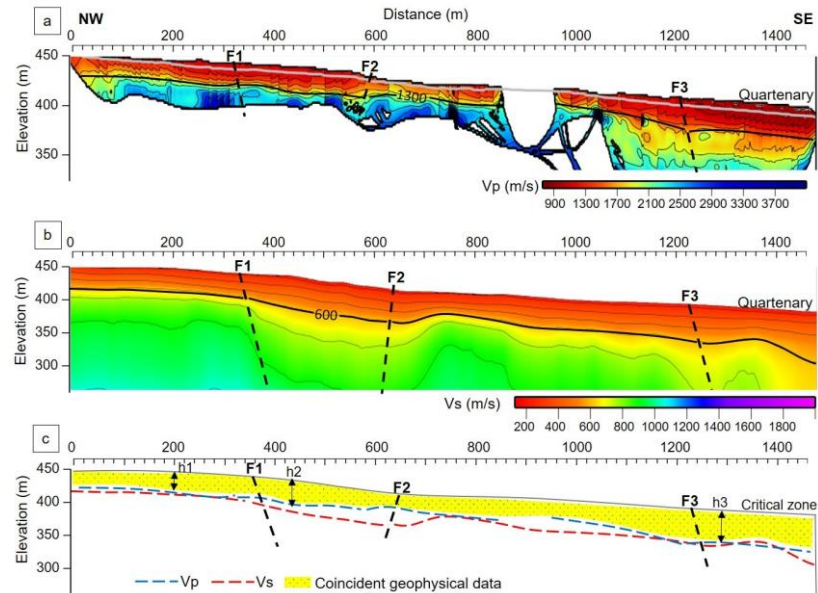


Figure 9. Geophysical imaging of La Salud South site with the interpretation proposed and details. (a) The Vp model from seismic tomography, (b) the Vs model from MASW, and (c) a joint comparison of the Vp and Vs results. The low velocity anomaly between F1 and F2 could correspond to the faultzone of the S-AMF.

The high-resolution Vp and Vs models presented here (Figure 10a,b) allowed us to precisely locate the contact of the most surficial geological units: (i) the Red Unit and Pleistocene-Quaternary alluvial fan deposits to the north of F2, and (ii) a weathered layer to the south of F2.

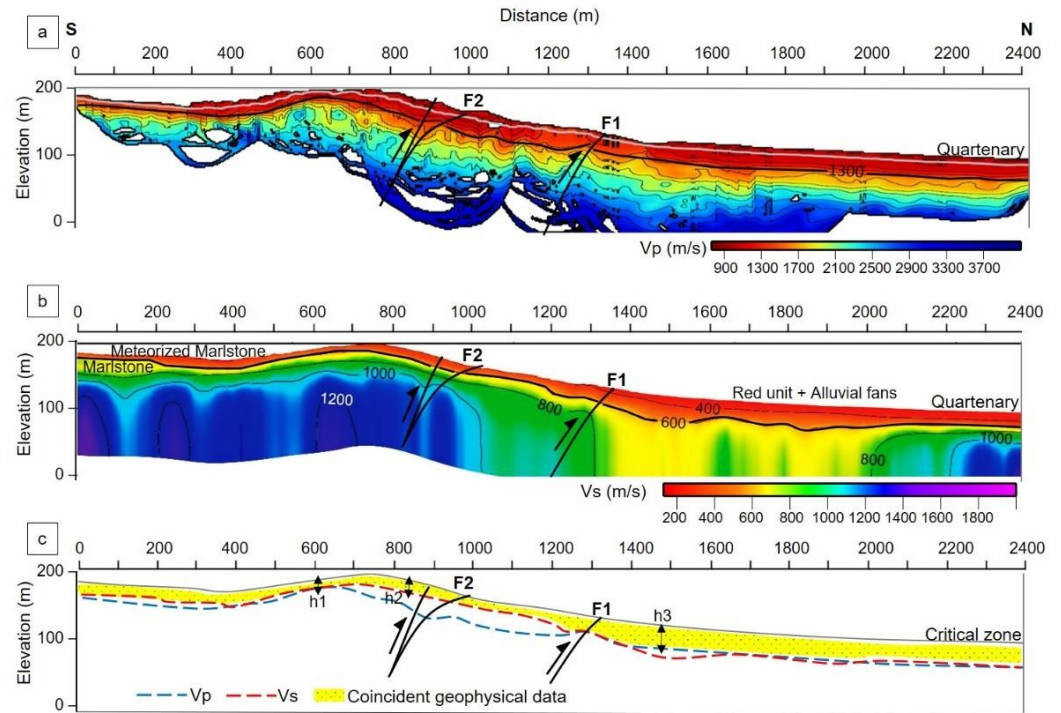


Figure 10. Geophysical imaging of Carrascoy site with the interpretation proposed and details. (a) The Vp model from seismic tomography, (b) the Vs model from MASW, and (c) a joint comparison of the interpreted CZ from both geophysical models. The low-velocity anomalies marked by F1 and F2 correspond to different thrust strands of the ACNF.

Towards the south, the CZ identified by the lowest velocities ($V_s < 600$ m/s and $V_p < 1200$ m/s) is located parallel to the topography at a depth of approximately 15–30 m at a distance of approximately 600 m (h1), close to the Red Unit outcrops until ca. 650 m. The Messinian rocks also have a very low seismic velocity, which could be associated with a weathered layer of marlstone. Taking a closer look at this layer (h2) in the elevated area towards the fault zone F2, it is relevant to point out this small thickness difference between h1 and h2. The CZ increases its thickness in 30–40 m in h2. The thickest point of the CZ is located at ca. 1300 m distance near fault zone F1 (h3). There, the Red Unit and the Pleistocene-Quaternary alluvial deposits feature a thickness of ca. 45–50 m. Between F1 and F2, only the rocks of the Red Unit crop out forming an anticline in the hanging wall of F1. In contrast to h1 and h2, the thickness of this shallow layer in the study area is strongly influenced by the overall oblique reverse deformation that characterizes the surroundings of the Algezares-Casas Nuevas fault, which influences the thickness of the CZ through the interaction of tectonic stresses with topography.

Implications and Discussion

The Advantages of Multi-Geophysical Measurements and Implications for the Interpretation of the CZ

Geophysical methods have numerous advantages for the characterization of the near-surface in terms of cost efficiency and depth accuracy (e.g., [76,77]). Geophysical methods can provide spatial boundaries to determine the maximum depth range of the CZ [22,23,78]. When deep marker information (e.g., well data) is not available, outcrop and trench data

can be combined with different geophysical methods to produce a robust model of the near-surface. For instance, P-wave tomography, Multichannel Analysis of Surface Waves (MASW), and Electrical Resistivity Tomography (ERT) are here used to minimize the ambiguity of the subsurface features. Each geophysical method used to determine the thickness of the CZ produces varying results in terms of vertical and lateral resolution. One approach involved the combination of the interpretation results from the multi-geophysical method to use the minimum thickness constrained by all the data as the final interpretation (as seen in, e.g., [74,75]). Future work could address the integration of the geophysical data using more advanced interpretation strategies, e.g., Machine Learning [79] or joint inversion [80].

Taking into account that the seismic profiles were originally designed for seismic reflection characterization, the quality of the first arrivals ensures the homogeneous distribution of the ray coverage along all profiles. It is important to highlight that the areas of poor coverage/gaps in ray coverage observed in some resulting velocity models (e.g., La Torrecilla, Figure 7b, and La Salud South, Figure 9a) are not related to the lack of data, but to the fact that these areas the acquisition geometry is far from a 2D geometry (mainly due to crooked pathways). The use of a fully 3D inversion code makes it difficult to obtain a good ray coverage in these areas when extracting the 2D velocity model along the seismic profile transects.

The interpretation of the CZ thickness in the La Torrecilla profile (Figure 7d) differs the most at ca. 250 m, where the ERT results point to a thicker CZ than the Vp and Vs models (h1). The three geophysical methods meet at a distance of ca. 620 m to provide the same thickness interpretation (h2). Meanwhile, at a distance of ca. 900 m, the ERT interpretation results matched Vp and shows a thicker CZ than that interpreted by Vs. Generally, the interpretation of Vs from MASW represents the distribution of the thickness of the CZ in the La Torrecilla profile as a minimum thickness than Vp and ERT. In the case of the La Salud North profile in Figure 8d, the interpretation of the Vp model represents the distribution of the CZ. The interpreted thickness of the CZ in the Vp model is slightly thinner than in the Vs model, and the result of the ERT interpretation is the thickest. The three geophysical methods meet in h1 at a distance of ca. 100 m and ca. 900 m facing SE. Meanwhile, Vp and Vs match in h2 at a distance of ca. 350 m and h3 at a distance of ca. 750 m.

From the La Salud South profile, the geophysical interpretation of the thickness of the CZ was obtained from the combination of Vp and Vs models (Figure 9c). The resulting CZ interpretation of the Vp model is slightly thinner than Vs and meets at some points, such as h1 at a distance of approximately 200 m and h3 at approximately 1300 m. In the Carrascoy profile (Figure 10c), the interpretation of the CZ is determined by the Vs result, similarly to the La Torrecilla profile (Figure 7d). The resulting interpretation of Vs is slightly thinner than Vp and meets at some points, such as h1 at a distance ca. 600 m and h3 at a distance ca. 1400 m.

The Impact of a Fault Zone, Elevation, and Topographic Slope on CZ Thickness

The presence of fault zones may have an effect on the thickness of the CZ. The presence of faults can lead to one of two outcomes: (i) a change in bedrock height levels caused by fault geometry changes, and (ii) an increase in the number of altered regolith layer fragments [19,22,23].

In this study, we have identified different fault zones in each profile by the combination of ERT, seismic tomography, and MASW models. The results in these models indicate that fault zones have a clear impact on the thickness of the CZ. For example, the thickness of the CZ in the La Torrecilla profile (Figure 7) coincides with the presence of a fault zone between F1 and F2, specifically the AMF shear deformation zone defined by Martínez-Díaz et al. [49]. The CZ surrounding the fault zone (h2) is thicker than the area outside the fault zone (h1 and h3). The thickness of the CZ in the La Salud North is also affected by the AMF shear deformation zone [49]. The thickest CZ in the La Salud North profile (Figure 8) is very close to the F1 fault (h2). Meanwhile, the thickening of the CZ in the La Salud South profile (Figure 9) appears close to the F3 fault, which is correlated to the S-AMF deformation zone

(h3). In the Carrascoy profile (Figure 10), the ACNF fault zone controls the thickness of the CZ, with the thickened layer located near the F1 fault zone (h3) [27,49].

The effect of elevation in the thickness of the CZ has been analyzed by Nielson et al., [81]. Their study reported that lower elevations correlated well with thicker CZ. In the La Salud South profile (Figure 9c), the lowest elevation on the SE (ca. 420–430 m) coincides with the thickest CZ (h3). The differences in elevation across La Torrecilla and La Salud North profiles are relatively small, and the thickness of the CZ is thus more controlled by the presence of the fault zone.

Different geophysical studies have identified differences in the thickness of the CZ depending on the topographic slope and orientation [8,25,78,82]. In our study area, especially in the Carrascoy profile (Figure 10b), the Vs model shows clear differences in CZ thickness in the topographic asymmetry area: the CZ thickness in h1 has a relatively lower topographic slope than in the h2 thickness (Figure 10c). This seems to indicate CZ thickness differences is depending on the orientation of the slope, where the north-facing CZ I (h1) is relatively thinner than the south-facing (h2). It could also depend on the lithology that the northern part is the Guadalentín Depression, which is a relatively thick basin.

Relationship between the Geological Units and the Cz Thickness

The thickness of the CZ is influenced by the type of rock. We attempted to investigate the relationship between the thickness of the CZ and the different geological units crossed by each profile. The results of the geophysical interpretation of the thickness of the CZ from the four study profiles are shown in Table 3.

Table 3. Relationship between CZ thickness and the different geological units that host it.

Profile	Geological Units	Minimum CZ (m)	Maximum CZ (m)	Average CZ (m)
La Torrecilla	Quaternary fluvial sediments and alluvial fan deposits (quartzites conglomerates and unconsolidated deposits formed by gravel, sands, silts, and clays).	30–40	50–60	40–50
La Salud North	Quaternary formations (alluvial gravels and siltstones).	30–40	40–50	35–45
La Salud South	Quaternary formations (alluvial gravels and siltstones). The Messinian rocks are associated with a weathered layer of marlstone as well as the Red Unit and Pleistocene-Quaternary alluvial fan deposits.	30–40	50–55	40–47.5
Carrascoy	Pleistocene-Quaternary alluvial fan deposits.	15–30	45–50	30–40

The CZ with the greatest average thickness is located in the La Torrecilla profile, with an average CZ thickness of 40–50 m. The CZ in La Torrecilla corresponds to Quaternary fluvial sediments and alluvial fan deposits (quartzite conglomerates and unconsolidated deposits formed by gravel, sands, silts and clays) [42,49]. In the La Salud North profile, the average CZ thickness of about 35–45 m corresponds to the Quaternary formations (alluvial gravels and siltstones). Similarly, in the La Salud South profile, the mean CZ thickness of about 40–47.5 m also corresponds to the Quaternary formations (alluvial gravels and siltstones). Alluvial fan deposits are important recorders of tectonic activity. Alluvial fans develop at the edge of the sedimentary basin, and this can be evidence of tectonic activity, with faults along the edge of the basin causing uplift in the catchment area and subsidence

in the basin. Therefore, it is possible to see evidence of tectonic activity in the alluvial fan depositional succession, where the massive influx of coarse detritus into alluvial fan deposits can be interpreted as the result of tectonic activity in the form of earthquakes and uplift [83,84].

The Carrascoy profile has the thinnest average CZ (around 30–40 m) and includes a weathered layer of Messinian marlstone and the Red Unit and Pleistocene-Quaternary alluvial fan deposits [42,49,85]. The marlstone rocks are interpreted as a shallow marine zone with a fairly massive concentration of carbonate deposits so that the clastic deposits are not thick enough in the Carrascoy profile. In the North of the Carrascoy profile, the presence of the Red Unit and Pleistocene-Quaternary alluvial fan deposits can explain why the CZ thickness in the Carrascoy profile deposits does not exceed the thickness of the other three profiles.

Finally, the values estimated for the thickness of the CZ in our study correlated well with the average 36.8 m thickness across continental areas estimated by Xu and Liu [11]. Therefore, we validate here the use of combined electrical and seismic methods to evaluate the thickness and characterize the CZ.

Conclusions

Geophysical methods, both seismic and electrical, have been used to map the distribution of the critical zone (CZ) laterally and vertically along the Eastern Betic Shear Zone (EBSZ). The CZ was mapped from the geophysical investigation in four different profiles: La Torrecilla, La Salud North, La Salud South, and Carrascoy. The P-wave tomography, MASW, and resistivity (ERT) models have provided valuable information to interpret the vertical and horizontal distribution of the shallow subsurface of active fault zones on profiles La Torrecilla and La Salud North. Similarly, the P-wave tomography and MASW methods were applied on profiles La Salud South and Carrascoy. The interpretation of these models allowed us to identify significant features of the subsurface: (i) the thickness of the CZ; (ii) the impact of the fault zone, elevation and topographic slope in the thickness of the CZ; and (iii) the relationship between the geological units forming the CZ and its thickness.

The final interpretation of the CZ thickness is the area where all the geophysical methods coincide. The CZ is identified along the profiles featuring low seismic velocity ($V_p < 1300$ m/s and $V_s < 600$ m/s) and high resistivity ($\rho > 200$ Ω m) and includes different fault zones. The thickness of the CZ varies along the profiles, with the average CZ thickness at La Torrecilla 40–50 m, La Salud North 35–45 m, La Salud South 40–47.5 m, and Carrascoy 30–40 m.

For complex locations where there is a combination of the fault zone and elevation differences, the thickness of the CZ may be controlled by one or both. In La Torrecilla and La Salud North, the CZ thickness is mostly controlled by the AMF shear deformation zone. In the La Salud South profile, the thickness of the CZ is more controlled by low elevation, with a thickness slightly larger than the CZ near the S-AMF shear deformation zone fault zone. Meanwhile, the thickest CZ in the Carrascoy profile is in the ACNF fault zone and has a low elevation. Based on the relationship between geological units and the thickness of the CZ, the CZ in the Carrascoy profile is the thinnest with the geological units in the form of marlstone, Red Unit, and Pleistocene-Quaternary alluvial fan. The La Salud North and La Salud South profiles are intermediate CZ composed of quaternary formations (alluvial gravels and siltstones). Then, the thickest CZ is on the La Torrecilla profile which is composed of Quaternary fluvial sediments and alluvial fan deposits (quartzite conglomerates and unconsolidated deposits formed by gravel, sands, silts, and clays).

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CHAPTER 7

DISCUSSION AND IMPLICATIONS

*“Real science can be far stranger than science fiction
and much more satisfying.”*
— Stephen Hawking

CHAPTER 7

DISCUSSION AND IMPLICATIONS

The outermost portion of the Earth, known as the Critical Zone (CZ), supports life and provides most of the resources we need for our activities and subsistence. Amongst other, the Critical Zone influences our society in the following aspects: the shaping of Earth's landscapes where people live; natural hazards; essential geological (minerals, energy, water) resources; short and long-term climate change biotic diversity. To understand these aspects and their influence it is required a holistic knowledge of the Earth's structure, nature and dynamics at different spatial and temporal scales [de Vries et al., 2018; IPCC 2018; IPBES 2019].

The research carried out and summarized in this memoir aims to contribute to answer a critical scientific question: What is the detailed configuration of major fault networks at the shallow subsurface and what are their linkage with the outermost layer of the crust where life, air, water and rocks interact? The critical zone (CZ) hosts a wide variety of hydrological, geochemical and biological processes that occur across multiple scales, thereby shaping landscapes, sustaining ecosystems and regulating resource availability. Therefore, the relevance of obtaining a 3D detailed view (including model grid) of the shallow subsurface in the vicinity of active fault zones is imperative. The multidisciplinary combination of different disciplines within the geoscience (e.g. structural geology, geophysics, geochemistry, geochronology, seismic and seismic fault-slip, surface kinematics and geodynamic modeling, etc.), should contribute to provide a comprehensive understanding of: fault zone behavior through time and in three spatial dimensions; the role of fluids and their interactions and feedbacks; slip behavior and evolution; and the development and evolution of faults. Therefore, new numerical models integrating composition, microstructure, fluid content, physical properties and, rates of processes in fault zones should contribute to bridge the gap between theory, the natural record,

and experimental laboratory data. This challenge has important potential applications in the mitigation of risks related to earthquakes, landslides and economic resources commonly associated with fissures and fault zones.

Within this framework, the main objective of this work has been to provide a multi-parameter model of the subsurface across a number of active faults within a band of deformation that includes the Alhama de Murcia main fault (AMF) zone. To cover most of the aspects addressing critical issues relative to the subsurface as indicated in the introduction and in the different contributions to the scientific journals, detailed models of the subsurface are mandatory. In this case, we have produced resistivity, P- and S- wave seismic propagation velocity models across different transects crossing the main fault zones within the Eastern Betic Shear Zone (EBSZ). The use of high-resolution Vs and Vp models, together with the surface geology information (trench and geological mapping) can help to increase confidence in hazard assessment studies and characterization (physical properties) including the thickness and lateral variations of the critical zone (CZ) [Miller et al., 1999; Rempe et al., 2014; Parsekian et al., 2015]. The analysis of surface waves to resolve a Vs model is the focus of the discussion to be developed in the current chapter. In particular the application of MASW complemented by the use of Vp tomographic models and resistivity to resolve the CZ and perform seismic hazard assessment.

7.1 Contribution of Vs models to seismic hazard assessments: 2D structural cross section across active fault

Among the contributions of geophysical studies to seismic hazard assessments is the mapping and characterization of fault zones, either previously identified or unknown faults (blind faults). Geophysical surveys are able to image [McCalpin, 2009] and generate models across them. In this memoir, model grids of seismic shear wave velocities derived from seismic dispersion characteristics of surface waves were obtained. The contribution of the high-

resolution shear wave velocity models where integrated with models from other geophysical parameters (V_p and/or resistivity) when analyzed in a fully integrated scheme provide new insights to the visualization of the internal structure of the active fault system, in this case in the EBSZ. Furthermore, the resolved models also positively correlated with the previous fault zone characterization studies carried out in the area using other geophysical and geological data such as: GPS data and trench studies [Martínez-Díaz et al., 2012; Martínez-Díaz et al., 2012a; Martín-Banda et al., 2016]. Geological constraints in the field are consistent with the proposed by the joint interpretations of V_s , V_p , and/or resistivity cross-sections (models). Fault zones that have been confirmed from previous studies are used as markers. Then, from the velocity model, fault zones are represented by low velocities (V_p and V_s) due to reduced bulk- and shear-modulus values in the fault plane and damaged areas. In addition, the resistivity is used to predict conductive zones that are associated with the presence of fluid in the damaged/fractured zone. The proposed V_s , V_p , and/or resistivity models helped to add constraints in the characterization of: i) fractured, damaged domains and main fault planes; ii) assess the implication of the active fault and fractured domains zones to high-risk areas, or highly deformed zones; iii) trace the continuity of deep blind fault structures to near-surface; and iv) make slip rate estimates.

7.1.1 Seismic signature of fault and fractured zones

Faults and their related damage zones (fault zones) feature variations in the physical properties that can be sensed by seismic methods [Ando and Yamashita, 2007; Iacopini et al., 2016; Martí et al., 2006b]. Fracturing and weathering reduce shear wave velocity and control surface wave dispersion [Miller et al., 2000; Xia et al., 1999]. Therefore, the velocity and dispersion characteristics of surface waves can be used to determine the variation of shear wave velocities with depth [Foti et al., 2018; Park et al., 1999]. The models derived reveal the 2D depth geometry configuration of the identified fault/fracture and the extent of their associated damaged zone.

Previous studies including empirical methods using laboratory data [Wang et al., 1978], seismic velocity from borehole geophysics [Boness and Zoback, 2004], controlled source seismic reflection [Alcalde et al., 2013; Catching et al., 2014, 2020; Martí et al., 2002a; 2006a; 2008], and earthquake data [Eberhart-Phillips and Michael, 1998; Thurber and Atre, 1993] reported a significant decrease in seismic velocities V_p and V_s within the fault plane and associated damaged zone, which can reach down to 50%. This decrease in seismic velocities most probably reflects the effect of the difference in the fracturing/weathering degree and the circulation of fluids. Thus, the damage zone features potentially higher hydraulic conductivity [Budiansky and O'Connell, 1980; Juhlin, 1995]. High hydraulic conductivity could significantly raise pore pressure, reducing effective stresses, decrease velocities, increasing attenuation, and amplifying the fracturing effect [Dvorkin et al., 1999; Siggins and Dewhurst, 2003].

The Guadalentín Depression is bordered to the north by the Alhama de Murcia Fault (AMF) and to the south by the Carrascoy Fault system (CAF). All these are part of a NE-SW left-lateral strike-slip fault system with a reverse component. The shallow geometry of the fractures part of this fault system constitute the target of this memoir. The geometry of fault zones and the internal architecture of the CZ are the addressed targets, using coincident seismic and electrical surveys. Four profiles are discussed: La Torrecilla, La Salud North, La Salud South, and Carrascoy. The geophysical characterization benefits from indirect geophysical methods, that include: V_s seismic velocity models derived from MASW, P-wave models derived from travel time tomography and/or Electrical Resistivity Tomography (ERT).

Seismic signature of fault and fractured zone, for instance in La Torrecilla profile (Fig.7.1), indicate the existence of two prominent fractures which have been interpreted (faults $F1$ and $F2$) which are identified by velocity discontinuities at values of V_s within the range of 500-800 m/s and V_p 's within the range of 1300-1800 m/s at a distance of $F1$ ca. 400 m and $F2$ ca. 520 m. These are consistent with the geometric location of the AMF fault system. Rock

samples of the fault have been characterized by gamma-ray (GR), P-wave velocity (V_p), S-wave velocity (V_s), and resistivity logs acquired within the FAM-1 borehole (Fig. 3, in Chapter 6) [Martínez-Díaz et al., 2012a; 2012b; Martínez-Díaz et al., 2018]. Furthermore, faults $F1$ and $F2$ also feature low resistivity $\rho < 50 \Omega\text{m}$.

We have also identified three blind faults which are indicated by the relatively low velocity domains with V_p within the range of 1200-2000 m/s and V_s in the range of 700-800 m/s at distance *ca.* 700 m ($F3$), *ca.* 900 m ($F4$), and *ca.* 250 m ($F5$). The most fractured/damaged zone in the La Torrecilla is located in the high-density fracture zones at a distance of *ca.* 350-900 m (in the center of line survey). The damage zone is characterized by a low velocity domain with V_p within the range of 1200-1700 m/s and V_s within the range of 400-700 m/s. The reduction in the V_s seismic velocity is indicative of a more tectonized or altered zone. Because of the high density of fractures these areas feature potentially high hydraulic conductivity. The relatively low V_p and V_s values reflect a decrease in shear modulus. This shear zone is defined by a 20 m wide band of well-developed fault gouge in the Alpujarride Complex of Permian-Triassic quartzites and phyllites, as well as sheared Upper Neogene marls, sandstone, and conglomerates [Martínez-Díaz et al., 2012a; 2012b; Martínez-Díaz et al., 2018].

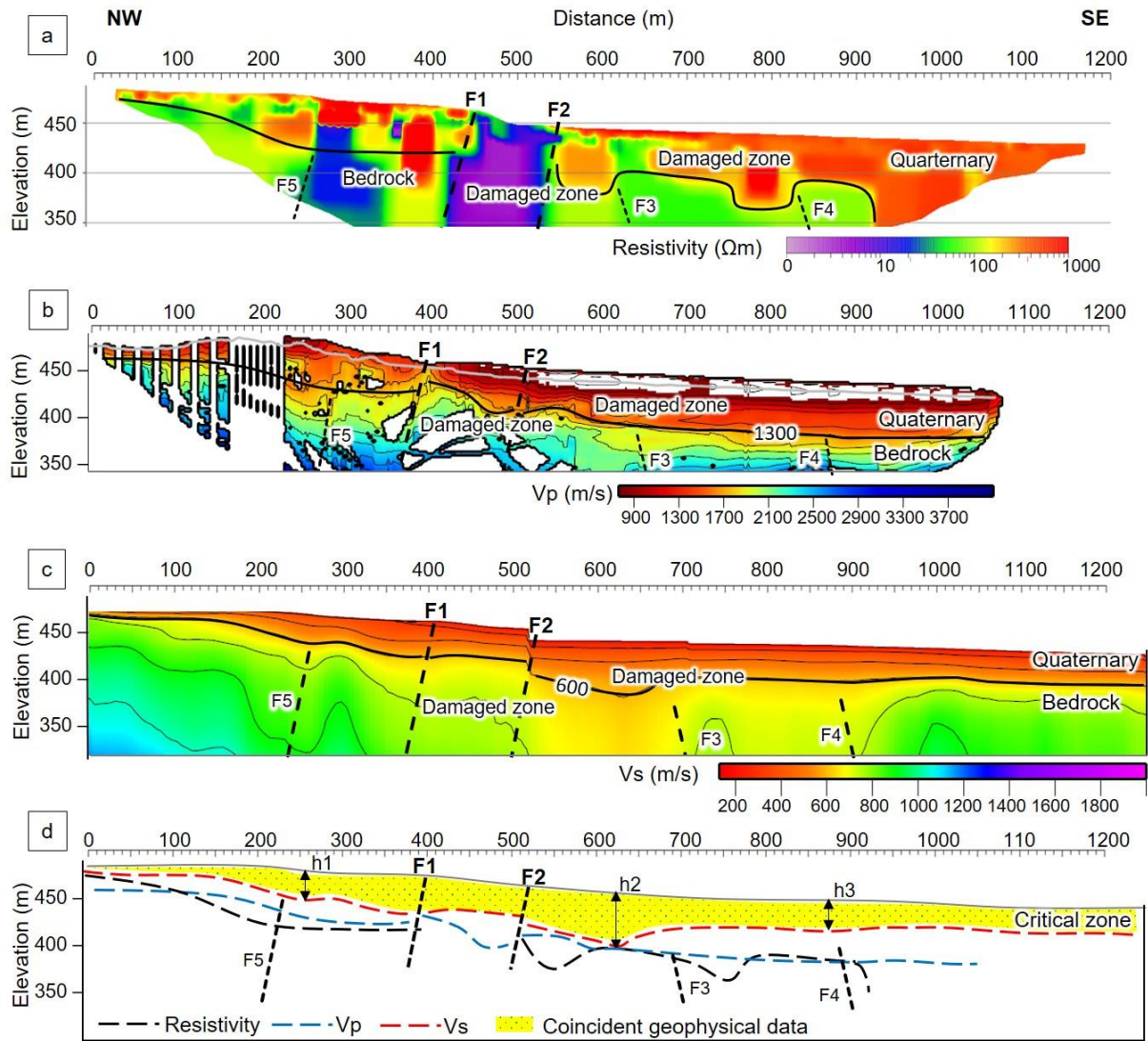


Figure 7.1. The image fault- and damaged- interpretations of La Torrecilla profile: a) The resistivity model; b) The P-wave velocity model; c) The S-wave velocity model; and d) The integration of geophysical interpretation of the base of CZ.

In summary, the structural interpretation of the V_p , V_s seismic velocities and resistivity models where the existing faults, blind faults, damaged/fractured zone, and CZ layer are indicated is shown in Fig. 7.2 for all surveys. From top to bottom: in La Salud North profile (Fig. 7.2a), the V_s model resolves the fault/fractured zone between $F1$ and $F2$ which is characterized by a Shear wave velocities V_s within the range of 600-1000 m/s and, V_p 's within 1300-1800 m/s. These damaged or fault zone is also characterized by resistivities of 80-130 Ωm . The $F1$ and $F2$ strands are linked to the S-AMF strand [Martínez-Díaz et al., 2003; 2012a;

2012b; Ferrater, 2016], which was also discovered through resistivity inversion from the magnetotelluric data [Martí et al., 2020]. We interpreted a blind fault (*F3*) at a distance of *ca.* 120 m that is characterized by the *Vp* and resistivity anomalies in the NW.

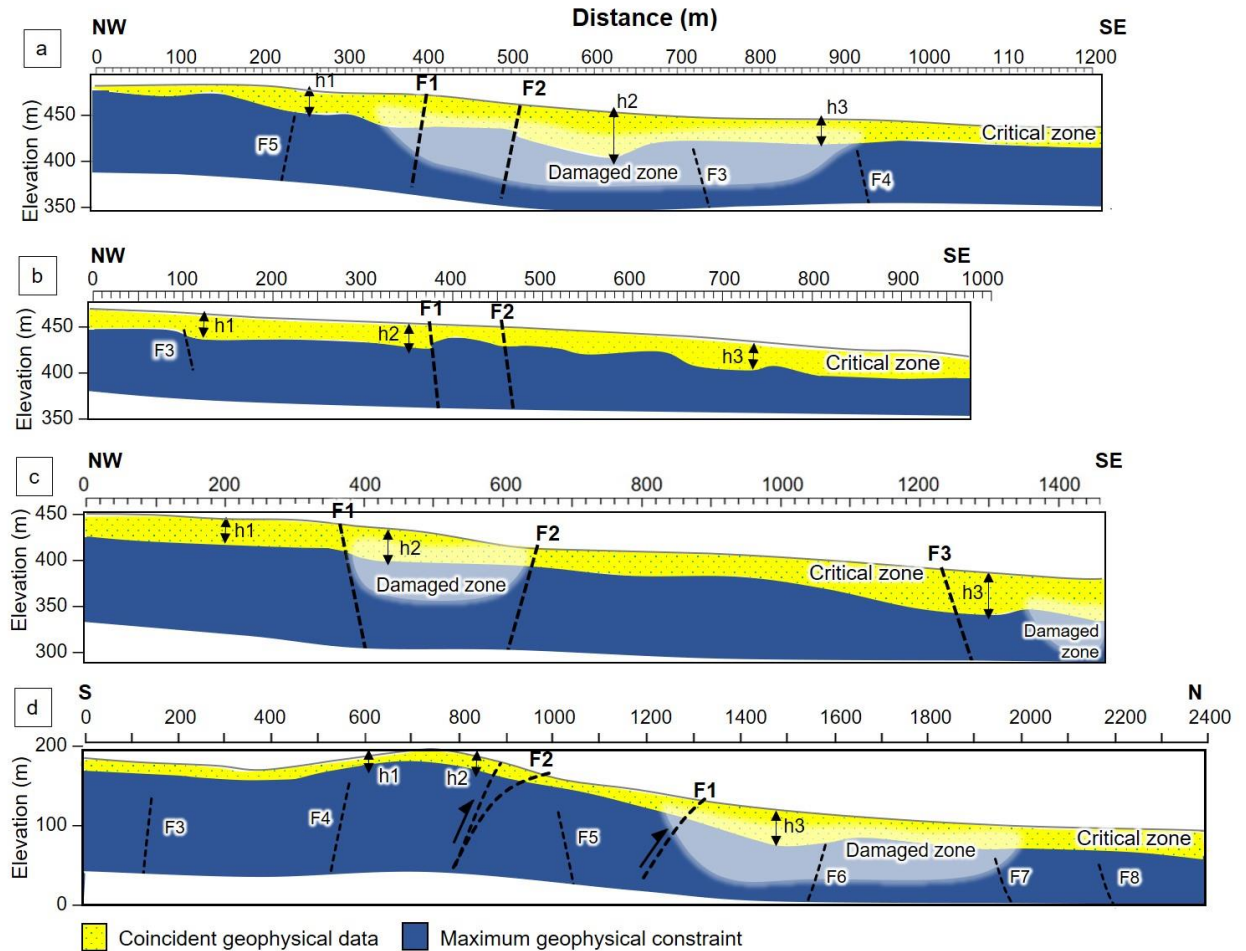


Figure 7.2. Composite figure illustrating the structural interpretation of the four transects across the EBZ at the different locations. These are joint/integrated interpretations of the different physical property models acquired along each transect. The interpretation of the geometry of fault- and damaged- zones. a) La Torrecilla profile; b) La Salud North profile; c) La Salud South profile; and d) Carrascoy profile. Yellow layer indicated the integration of geophysical interpretation of the base of CZ.

In the La Salud South profile (Fig. 7.2c), the low-velocity domains of the model fall within velocity ranges for *Vs* between 600-1000 m/s and *Vp* between 1300-1800 m/s these are interpreted as faults zones at a distance of *ca.* 310 m and *ca.* 600 m defined by the fault planes

F1 and *F2* that correlate with the outcrop of the S-AMF strand [Martínez-Díaz et al., 2003; 2012a; 2012b; Ferrater, 2016]. The fault *F3* is also mapped at a distance of *ca.* 1200 m in the SE of the line survey. Meanwhile, no blind faults were identified in the La Salud South profile by *Vp* and *Vs* models.

Focussing into the CZ, it is mostly defined by a relatively low *Vs* velocity layer with variable thickness, under CZ at a distance of *ca.* 400-600m (between *F1* and *F2*) and *ca.* 1350-1450 m (close to *F3*) are interpreted as damaged zones. The damaged zone is characterized by low velocity layer *Vp* 1200-1700 m/s and *Vs* 600-700 m/s, interpreted as an area where a reduction of the *Vs* may indicate a more tectonized or altered/damaged zone. Damage volumes are consistent with highly fractured/altered zones featuring potentially higher hydraulic conductivity raising the pore space, and decreasing seismic *Vs* velocity values. Such altered rock values increase attenuation of seismic energy. Small decrease of *Vs* velocity has been identified at these locations. That could be related to the AMF strand (the fault zone mapped in this area) most probably branch of the AMF fault system [Martínez-Díaz et al., 2003; 2012a; 2012b; Ferrater, 2016].

The high-resolution seismic velocity models presented in Carrascoy profile allow us to identify the structure of the strands of the Algezares-Casas Nuevas Fault (Fig. 7.2d) [Martín-Banda et al., 2016]. The faults *F1* and *F2* are relatively low-angle oblique reverse faults that displace the Red Unit (Unidad Roja) and the middle-upper Pleistocene alluvial fans and, therefore, with activity during the Quaternary [Martín-Banda et al., 2016]. *F1* is positioned at a distance of *ca.* 1400 m and *F2* at a distance of *ca.* 900 m base on their outcrops. According to the *Vp* and *Vs* models, *F1* is depicted, following the surface outcrops, as most probably dipping to the south down to a depth of *ca.* 80-100 m consistent with the geometry of the velocity anomalies *Vp* 1700-2000 m/s and *Vs* 600-800 m/s. Meanwhile, near the surface (Unidad Roja-

Messinian contact), the *F2* fault is characterized by velocity values of V_p 1500-2000 m/s and V_s 600-800 m/s at a depth of 150 m from the surface.

In addition, two blind faults *F3* (ca. 200 m) and *F4* (ca. 600 m) to the south of *F2*, one blind fault *F5* (ca. 950 m) between *F1* and *F2* are also suggested by mapped by the low velocity anomalies. In addition to the outcropping strands of the Algezares-Casas Nuevas Fault, we interpret the presence of a number of blind faults, with complex geometry: some are interpreted as south vergent thrusts these are identified as *F3* (ca. 120 m), *F4* (ca. 500 m), and *F6* (ca. 1550 m), and a few others dipping towards the N: *F5* (ca. 1050 m), *F7* (ca. 1950), and *F8* (ca. 2200 m). The high density of blind faults in the Carrascoy profile would represent a strongly damaged zone at a distance of ca. 1300-2000 m clearly visible by the low V_s velocity domain with velocities within the range 600-900 m/s. The low velocities would then be related to fracturing and local weathering that would reduce the shear modulus value and associated to weathering bedrock (fractured zone).

7.1.2 Fault and fractured/damaged zones and, hazard assessment

Within the determined V_s model, low-velocity domains are indicative, most probably, of damage zones, within the hard rock, weathered bedrock, and soil cover at shallow depth. Damaged and/or highly physically altered rock domains feature higher porosity and more likely increases the permeability (hydraulic conductivity) these increases the attenuation of the seismic waves while propagating through these domains.

V_s is strongly influenced by the shear modulus and V_p is strongly influenced by the bulk modulus [Eberhart-Phillips and Michael, 1998; Thurber and Atre, 1993]. Based on the National Earthquake Hazard Reduction Program (NEHRP) description for site characterization (Table 2 in Chapter 5), the damaged zone near the surface levels of the profile would be consistent with moderately weathered to weathered sedimentary rocks (Types IV and V in Table 2). In

addition, the higher the fracture concentration, the greater the degree of weathering interaction, and therefore the lower the resulting V_s .

Two relatively important elements that have the potential of enhancing the destructive capacity of a seismic events have been identified and characterized throughout this memoir in the study area: the location (and density) of fault zones and the thickness of the sedimentary, unconsolidated cover. Ground shaking due to seismic waves during a significant earthquake, at a specific location, will shake buildings or structures at that location. Shaking will be generated by the body waves (P- and S- waves) and, by surface waves (Rayleigh and Love waves). Previous studies have demonstrated that destructive earthquakes can cause much more extensive damage at unconsolidated areas than at sites characterized by solid consolidated bedrock. [Shaw and Suppe, 1996; Fletcher and Wen, 2005]. Furthermore, sedimentary layers have low-seismic velocities in general, which cause time delays for seismic waves when the thickness of the sedimentary rock is relatively large on the order of hundreds of meters [Ni et al., 2014; Bao et al., 2019]. The amplification of the local ground motion is controlled by; lithological properties of the sedimentary infill; sharp seismic velocity contrasts; variations in sediment thickness and basement topography in tectonically active areas, these aspects are critical for seismic hazard analysis [Field and Jacob, 1993; Graves et al., 1998; Hartzell et al., 2016]. Surface ground motions can be strongly amplified if geological conditions are unfavorable (e.g. sediments) [Semblat et al., 2009]. Places where there are relatively thick unconsolidated sedimentary deposits underneath will suffer higher shaking amplitudes, at the same distance and from the same earthquake, than places where there is solid bedrock underneath [Field and Jacob, 1993; Graves et al., 1998; Hartzell et al., 2016]. It is beyond the scope of this thesis to carry out a seismic hazard assessment, but identifying the presence and characteristics of fault zones and the reach of the sedimentary cover will be helpful in future seismic hazard assessment of the study area.

Based on the description in fault identification and damaged zone characterization of all profiles, within the EBSZ the areas within the neighborhood of the Carrascoy and La Torrecilla profiles can be classified as areas with a higher hazard than the areas within the neighborhood of La Salud North and La Salud South transects. The Carrascoy profile shows the thickest damage zone and the higher density of interpreted fractures, and therefore it is the area most prone to seismic hazard (Fig. 7.2d). At this location, the fracture activity is controlled by the ACNF Fault, as a strand of Carrascoy Fault System [Martín-Banda et al., 2016]. The six blind faults identified by our models in this area could imply that the stress is more distributed in this area, although additional data from INSAR and/or GPS is required to quantify this phenomenon. In any case, the seismic data is indicative that this area is highly tectonized or altered, with a higher level of maturity. In addition, the sediment layer at distance of *ca.* 300-700 m in the hanging wall *F2* is relatively thin on the order of 15 to 30 m. Meanwhile, at a distance of *ca.* 1300-2000 m, the sediment layer is thicker on the order of 30 to 50 m.

La Torrecilla profile also has a high-density of fault zones/damage areas. A conspicuous fault zone can be correlated with a low resistivity anomaly at a distance of *ca.* 400-500 m, interpreted to be bounded by faults *F1* and *F2* (Fig. 7.2a). This zone which is located in the hanging wall of the AMF shear deformation band, shows a sediment thickness of approximately 30 to 50 m. This layer consists of graphitic mica-schists and quartz-schists [Martínez-Díaz et al., 2018; Gómez-Novel, 2021]. In the same profile, at a distance of *ca.* 550-900 m, a thicker sedimentary layer ranging from 40 to 60 m consisting of alluvial fan deposits and fluvial sediments likely presents a higher risk than Northern part along the profile if ground shaking occurs at this location [Martínez-Díaz et al., 2018; Gómez-Novel, 2021].

In La Salud South, the damage zone interpreted to be located at a distance of *ca.* 350-500 m (between faults *F1* and *F2*, Fig. 7.2c) with a sediment layer thickness of 40 to 50 m consisting of sedimentary rocks from the Guadalentín Depression (mainly marls and gypsums)

and the Paleozoic rocks from the Alborán Domain (phyllites, quartzites and schists) [Ferrater et al., 2017; Martínez-Díaz et al., 2012a; 2018]. Meanwhile, La Salud North and South profiles are located in relatively stable areas, with no fractured zones identified in La Salud North profile (Fig. 7.2b). Tectonic processes in the La Salud South and La Salud North profiles appear to be controlled by the S-AMF Fault, which is a branch of the AMF Fault [Martínez-Díaz et al., 2003; 2012a; 2012b; Ferrater, 2016], this may indicate low stress levels in this area.

7.1.3 Constraints on the location and geometries of blind faults

As one of the contributions to aid SHAs, the combination of Vp and Vs models can provide a complete picture of the fault zone geometry at depth. In some cases, the near-surface fault zone is not detected by the Vp model, but its combination with the Vs model can contribute to complement shallow features mapped in the near surface that the Vp model cannot resolve.

For example, in Fig. 7.3, along the cross-section of the Carrascoy transect the Vp model, the blind faults identified by the Vp model do not extend to the surface, i.e. they remain buried. For example, fault *F3* was identified from -50 m below sea level to position *ca.* 50 m above sea level, fault *F4* is interpreted from -80 m below sea level to position *ca.* 30 m above sea level, fault *F5* is mapped from *ca.* -50 m below sea level to *ca.* 50 m above sea level, and fault *F6* to *F8* are mapped at about -120 m to -30 m below sea level. However, when using the Vs model, the continuity of each blind fault (*F3* to *F8*) can be traced up to the near surface, at least until the base of CZ (Fig. 7.3c). Joint Vp and Vs models are therefore more powerful and provide a more complete picture of the fault system at depth.

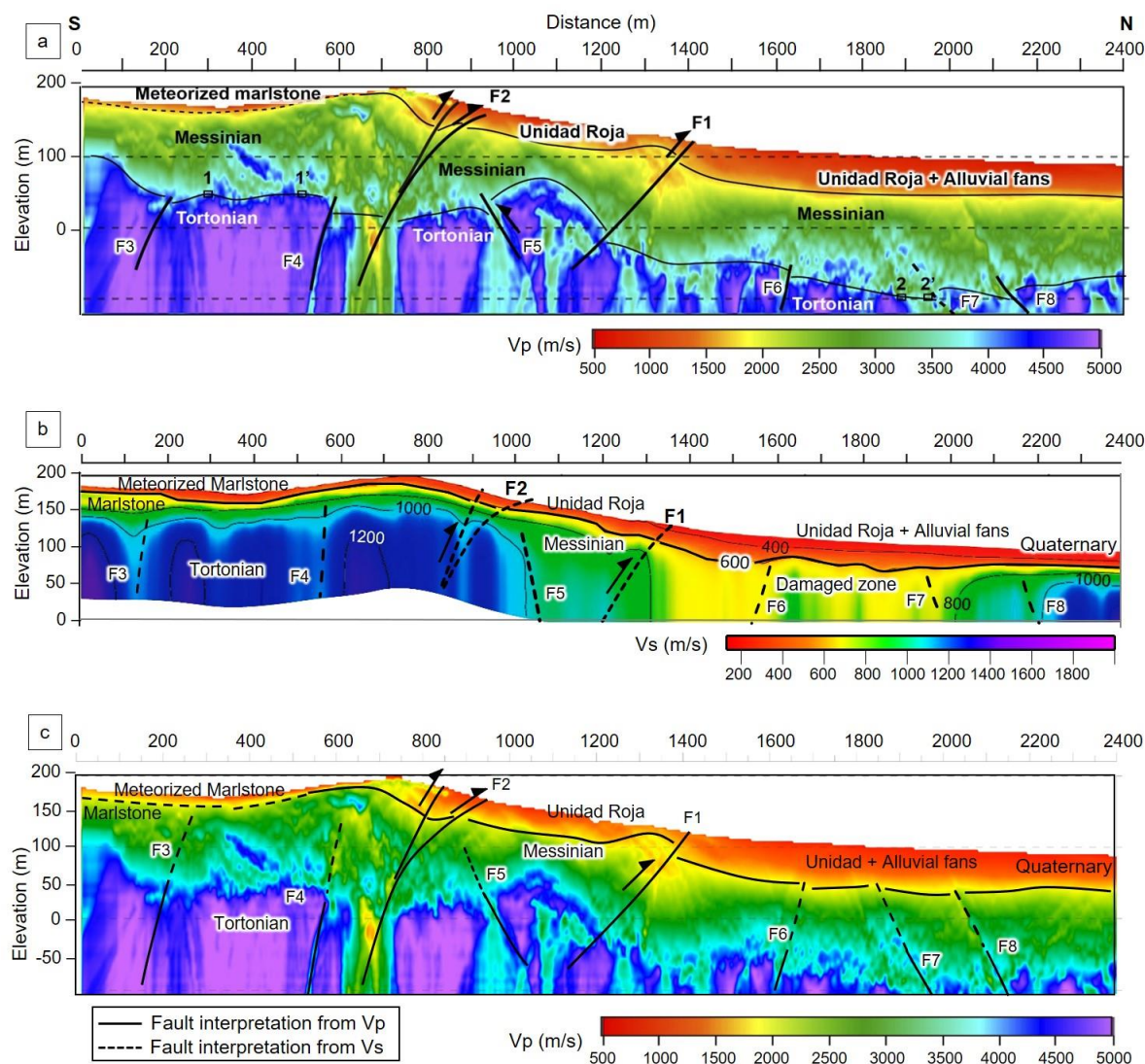


Figure 7.3. a) The P- wave velocity model and its interpretation; b) The S-wave velocity model and shallower interpretation; and c) The integration of V_p and V_s interpretation of the fault zones.

7.1.4 Estimates of Slip rates

The rocks of the Unidad Roja form an anticline in the hanging wall of $F1$ (between $F1$ and $F2$) of the Carrascoy profile (Fig. 7.3a). In the southern strand, $F2$ may be formed by several branches which may merge at ca. 30-40 m above sea level, producing the monocline structure observed in its hanging wall. This monocline could be linked to a blind fault on the Messinian-Tortonian contact at a distance of ca. 600 m and at ca. 0 m above sea level that in turn may have led to a change in the bedrock altitude levels, with implications for the distribution

and value of the tectonic stress field in the sub-vertical direction to the surface. Furthermore, by identifying the Messinian/Tortonian and Unidad Roja/Messinian contacts in both blocks of the Algezares-Casas Nuevas Fault, we could estimate an apparent vertical slip rate knowing that the fault formed around 209.1 ± 6.2 ka [average value from Martín-Banda et al., 2016]. Specifically, the Messinian/Tortonian contact apparent vertical displacement from one block to the other is quoted in 135 ± 15 m (points 1 and 1' respect to points 2 and 2' in Fig. 7.3a). This displacement is consistent and practically identical, 140 ± 20 m, taking as reference the Unidad Roja/Messinian contact respect to the base of the outcrop of the Messinian on the upthrown block located southwards of the seismic profile.

Considering these displacements accumulated since the onset of fault activity in 209.1 ka, we calculate a vertical slip rate of 0.66 ± 0.06 m/ky, considering the error propagation from the displacement measurements as well as for the time. This value is slightly higher than the 0.34 ± 0.02 m/ky [Ferrater et al., 2017] and 0.37 ± 0.08 m/ky estimated by Martín-Banda et al. [2016], and lower than the 1.3 ± 0.2 m/ky, calculated based on GPS data in the Alhama de Murcia Fault [Echeverría et al., 2013]. However, our estimated value is very similar to the 0.64 ± 0.4 m/ky established for the net slip rate along the NE Segment of the Carrascoy Fault for the last 220 ky (similar period) [Martín-Banda et al., 2021].

This difference in slip rate calculation is not surprising, as previous values were calculated in a different part of the same fault, where the Algezares-Casas Nuevas Fault has one major strand, and according to trench data restitution of the top of the Unidad Roja [Martín-Banda et al., 2016]. The apparent displacement of the Messinian-Tortonian contact in an area where the Algezares-Casas Nuevas Fault depicts a complex geometry of fault strands that may have played a role in displacing the Messinian-Tortonian contact is used to calculate slip rate estimation.

7.2 Shear wave velocity models (Vs) and the Critical Zone

In the developed approach, near-surface Vs-depth models are retrieved from Surface waves (Rayleigh) by inversion of their dispersion curves as described in the preceding chapters. When multiple shot gathers along a transect are available, the 1D Vs-depth profiles obtained for every shot gather can be pasted together to construct pseudo 2D Vs-depth model so that lateral variability is mapped. To account for the lateral heterogeneity, other techniques have been proposed, including cross-correlation assessment of multichannel data, spatial filtering domain, and laterally constrained inversion [Bohlen et al 2004; Socco et al 2009; Bergamo et al 2012; Ikeda et al 2013; Foti et al 2018]. These techniques contribute in somewhat more detail for resulting in slightly higher -resolution 2D Vs-depth models. They are more appropriate for stratified laterally smooth layering, due to the a-priory established hypothesis and constraints. In any case the development used in this memoir is appropriate in order to determine the model of the subsurface and is able to establish constraints on the CZ layer.

The use of MASW in characterization of the CZ as it is used in this memoir is relatively new, which provides this work with some innovation flavor. The characterization of the subsurface by using Vs models can contribute to provide high-resolution velocity models of the CZ, to reveal subsurface features within the range of meters to tens of meters (i.e. shallow exploration). In the produced Vs models, the CZ can be described as a low velocity layer with variable thickness. The Vs velocities are sensitive to sediment composition (and also: fracture density, consolidation, existence of fluids) beneath the surface and add key constraints to characterize the nature of the subsurface structures providing significant additional constraints that can be used in conjunction to reduce uncertainty [Befus et al., 2011; Parsekian et al., 2015; and Pugin et al., 2009]. There are numerous studies demonstrating geophysical measurements can handle different spatial scales and the entire depth range of the CZ [Parsekian et al., 2015; Flinchum et al., 2022]. The great challenge is how the Vs method can image the

sub-layering or internal structure of the CZ (layer thickness) in a small-scale (first 10 meters) and constrain the geometry of the base of the CZ.

The following fundamental issues regarding CZ architecture remain to be addressed [Parsekian et al., 2015; Flinchum et al., 2022]: (1) What is the thickness of the CZ? (2) What is its detailed internal structure; does it have distinct layers and boundaries? and (3) If so, how thick and how well-defined are they, and, finally, how do they vary geographically (landscape) and with the geological structure (tectonic environments) at the subsurface (Fig. 7.4)? The answers to these questions are critical for testing hypotheses about the mechanisms that create and maintain the CZ. The research documented within this memoir involves the geophysical characterization of the shallow subsurface and therefore, this section aims to describe the outputs or the developed research concerning the CZ: i) the contribution of Vs models; ii) the effect of fault zone on the thickness of the CZ; iii) the topographic slope impact on the thickness of CZ; and iv) the relationship between the geological units and the CZ thickness.

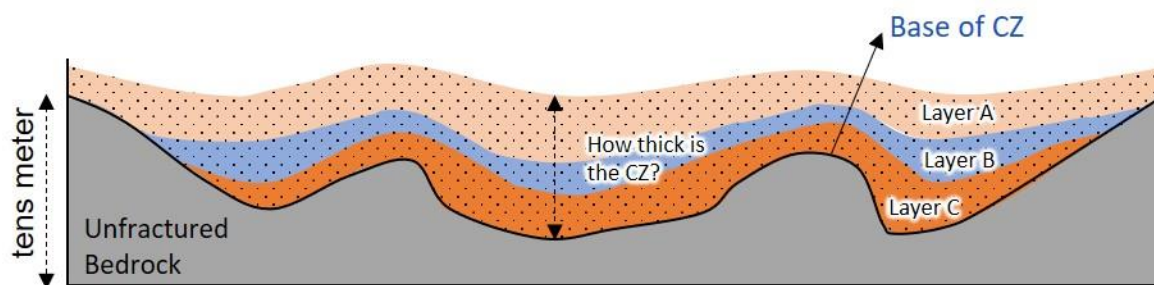


Figure 7.4. Illustration of the primary goal of CZ characterization. The fundamental unresolved issues which are strongly dependent on the geographical location and the local geology which directly affect the CZ. Thus, they are major issues targeted by research devoted to the characterization of the shallow subsurface (internal structure of CZ, overall thickness, physical properties, influence of fault damaged zone within the internal structure of the CZ, among other issues) [Parsekian et al., 2015; Flinchum et al., 2022].

7.2.1 The contribution of Vs to imaging of CZ

The Vs models derived from the analysis of surface waves can help to constrain the internal structure of the CZ in the study areas. The Vs field is able to constrain features down to < 10 meters thickness, where the internal sub-layering of the CZ is not well constrained by the Vp models derived from seismic refraction methods [Parsekian et al., 2015; Flinchum et al., 2022]. The P-wave velocity model, on the other hand, help constrain, or quantify the total thickness of the CZ across landscapes spanning hundreds of meters.

In relation to the resolution capabilities of the Vs models derived from MASW, there are studies that are capable to estimate the thickness of soil distribution within meters to tens of meters [Befus et al., 2011; Yaede et al., 2015; Lu et al., 2017]. In this memoir, based on the penetration depth criteria described in Chapter 4, the Vs penetration of this study can reach subsurface depths ranging from approximately ~2m (small-scale) to ~150m (large-scale).

For instance, in La Salud South profile, the distribution of sub layers of CZ are well imaged (Fig. 7.5). However, sub-meter sediment thicknesses cannot be constraint. In the Vs model, velocities < 200 m/s can indicate unconsolidated sediment, weathered layer corresponding to the shallowest 10 m; velocities between 200 to 400 m/s within the first 20 m, might indicate the influence of compaction and, velocities in between 400 m/s to 600m/s might indicate further compaction usually happening within the first 35 m [Jones et al., 2003; Brain, 2016; Pelletier et al.2016].

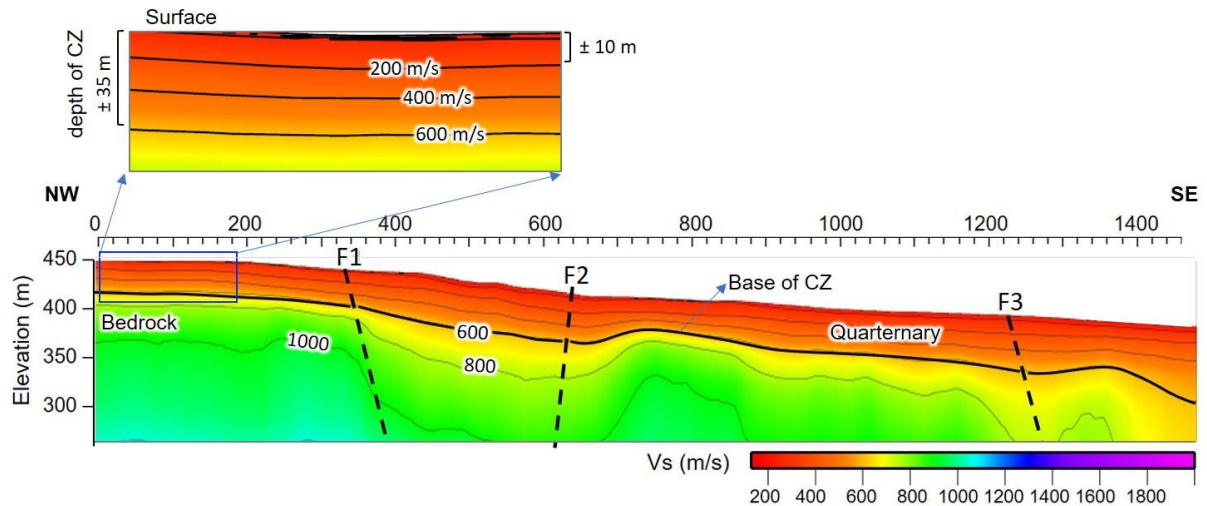


Figure 7.5. The Vs profile and the interpretation of the La Salud South profile. Detail inset illustrating the thickness sub-layer of the CZ.

7.2.2 Fault zone effect on CZ thickness

The high-resolution Vs models produced allow the identification of CZ thickness variations that can reach over ~ 50 m in the neighborhood of active fault zones. In the La Torrecilla profile (Fig. 7.2a), the Vs-depth profile reveals a CZ layer that varies laterally from the thinnest 5-10 m at a distance of *ca.* 0-100 m to the thickest ~ 50 m at a distance of *ca.* 600-700 m in the middle of the profile. The thickness increases of the CZ in the La Torrecilla profile is consistent with the presence of a fault-bounded structure between *F1* and *F2*, this appears to correlate with the AMF shear deformation zone defined by Martínez-Díaz et al. [2012]. Along the Carrascoy transect (Fig. 7.2d), the CZ surrounding the fault zone (*h2*) is thicker than the area outside the fault zone (*h1* and *h3*).

The Vs velocity model imaged the CZ layer in the La Salud North transect, with the thinnest part of the CZ being 30-40 m at a distance of *ca.* 500-600 m and the thickest being ~ 50 m at a distance of *ca.* 700-800 m (Fig. 7.2b), which is located in the area characterized by relatively low elevation (marked by *h3*). In the La Salud South profile (Fig. 7.2c), the thickness distribution of the CZ layer is relatively parallel to the surface, with a thickness range of 30-50

m. The thickest CZ in the La Salud South profile appears close to fault *F3* at a distance of *ca.* 1200-1300 m where the profile features a relatively low topographic slope.

The contact boundary between the CZ and the bedrock was identified within the Carrascoy profile (Fig. 7.2d). The low *V_s* velocity corresponding to the CZ layer, can be clearly identified to be of a thickness < 15 m at a distance of *ca.* 0-100 m (*h1*), a thickness 10-20 m at *ca.* 500-700 m (*h2*), a thickness within 20-30 m at a distance of *ca.* 800-1000 m, and the thickest part of the CZ which reaches values of ~50 m at distances of *ca.* 1400-1500 m. In the Carrascoy profile, the ACNF fault zone controls the thickness of the CZ [Martín-Banda et al., 2016], with the thickest part of the layer located near the *F1* fault zone and a relatively low topographic slope (*h3*). The damage zones associated to the fault result in a rise in the number of regolith layer fragments [Holbrook et al., 2014; Clarke et al., 2011; Slim et al., 2015]. According to these descriptions, there is a relatively good correlation between the thickness of the CZ layer and the fault zones, with the CZ layer near the fault zone being relatively thicker than locations far from the fault zone. The *V_s* model includes what is considered to be the CZ in the damage zone (within the neighborhood of the faults), thus revealing changes in the level of consolidation (more solid) bedrock.

7.2.3 Topographic slope impact on the thickness of CZ

Various geophysical studies devoted to the characterization of the CZ have found that the thickness of this layer varies depending on the topographic slope and orientation [Anderson et al., 2014; Clair et al., 2015; Befus et al., 2011; Anderson et al., 2004]. The *V_s* model in our study area, particularly in the Carrascoy profile (Fig. 7.6) roughly oriented SE to NW, shows clear differences in CZ thickness evidencing the topographic asymmetry. The CZ thickness in *h1* has a lower topographic slope than the CZ thickness in *h2*. This appears to indicate that CZ thickness varies depending on slope orientation, with south-facing CZ (*h1*) being relatively

thinner than north-facing CZ (h_2). However, this feature is further influenced by the variations in lithology. The latter corresponding to the Guadalupe Depression, a relatively thick basin.

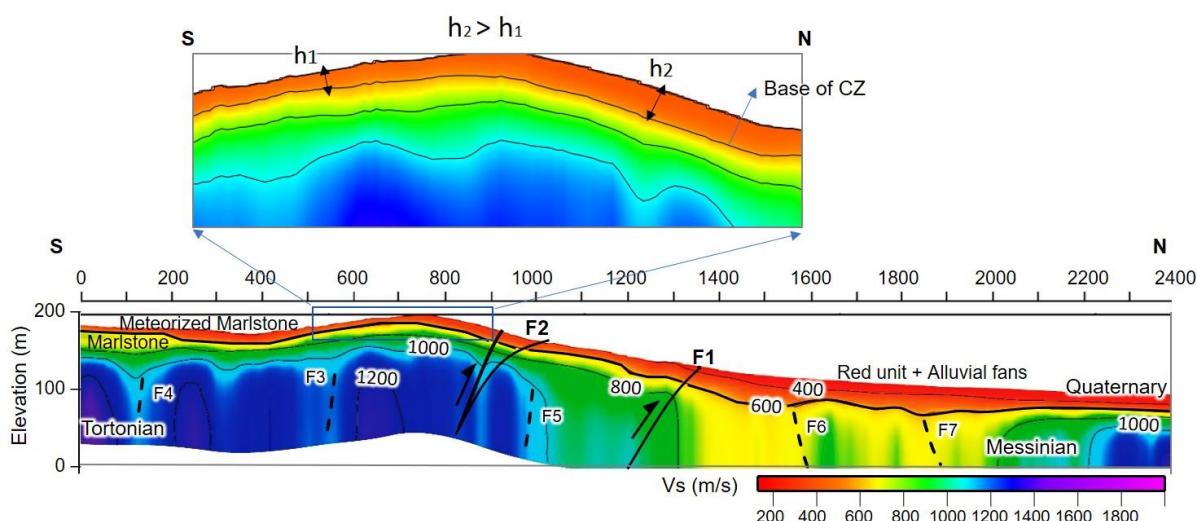


Figure 7.6. The Vs velocity model and the interpretation of the Carrasco profile. Top: detail inset illustrating the thickness differences between the south facing h_1 and the north facing h_2 CZ layer. This may indicate the mapped thickness differences in the regolith depending on the orientation of the slope as identified in other studies [Anderson et al., 2004; Anderson et al., 2014; Befus et al., 2011; Clair et al., 2015].

7.2.4 Relationship between the geological units and the CZ thickness

The thickness of the CZ is strongly influenced or dependent on the type of rock. We attempted to investigate the relationship between CZ thickness and the geological units traversed by each profile. Table 7.1 shows the results of the geophysical interpretation of the thickness of the CZ from the four studied profiles.

The CZ with the greatest average thickness is discovered in the La Torrecilla profile, where the CZ features on average a thickness of 40-50 m. The CZ in La Torrecilla profile corresponds to Quaternary fluvial sediments and alluvial fan deposits (quartzite conglomerates and unconsolidated deposits formed by gravel, sands, silts and clays) [Martínez-Díaz et al., 2012; Martínez-Pagán et al., 2018]. In the La Salud North profile, the average CZ thickness is on the order of 35-45 m. Lithology corresponds to the Quaternary formations (alluvial gravels

and siltstones). Similarly, in the La Salud South profile, the mean CZ thickness of about 40-47.5 m also corresponding to the Quaternary formations (alluvial gravels and siltstones) [Martínez-Díaz et al., 2012].

Alluvial fan deposits are important tectonic activity recorders. Alluvial fans form at the edge of sedimentary basin, which can evidence the tectonic activity, with faults along the basin's edge causing uplift in the catchment area and subsidence in the basin. As a result, evidence of tectonic activity can be found in the alluvial fan depositional succession, where the massive influx of coarse detritus can be interpreted as the result of tectonic activity in the form of earthquakes and uplift [Heward, 1978; Nichols, 2009].

Table 7.1. A summary of the relationship between CZ thickness and geological units

Profile	Geological Units	Minimum CZ (m)	Maximum CZ (m)	Average CZ (m)
La Torrecilla	Quaternary fluvial sediments and alluvial fan deposits (quartzites conglomerates and unconsolidated deposits formed by gravel, sands, silts, and clays).	30-40	50-60	40-50
La Salud North	Quaternary formations (alluvial gravels and siltstones).	30-40	40-50	35-45
La Salud South	Quaternary formations (alluvial gravels and siltstones).	30-40	50-55	40-47.5
Carrascoy	The Messinian rocks are associated to a weathered layer of marlstone and the Red Unit and Pleistocene-Quaternary alluvial fan deposits.	15-30	45-50	30-40

The Carrascoy profile features the thinnest average CZ and contains a weathered layer of Messinian marlstone, the Red Unit, and Pleistocene-Quaternary alluvial fan deposits (30-40 m) [Martínez-Díaz et al., 2012; Martínez-Pagán et al., 2018; Martí et al., 2020]. The marlstone rocks are interpreted as a shallow marine zone with a fairly massive concentration of carbonate deposits, so that the clastic deposits in the Carrascoy profile are not thick enough. The presence

of the Red Unit and Pleistocene-Quaternary alluvial fan deposits to the north of the Carrascoy profile can explain why the thickness of the CZ in the Carrascoy profile deposits does not exceed the thickness of the other three profiles. Overall, the thickness of the CZ estimated in our study correlates well with the average thickness of 36.8 m across continental areas estimated by Xu and Liu [2011].

Finally, the geophysical integration of the MASW in combination with P-wave tomography and/or Electrical Resistivity Tomography (ERT) methods are an asset in the characterization of the shallow subsurface structures, especially in active fault systems and or deformation bands. This detailed analysis allowed us to assess the extent to which this combination of methods could be used to successfully map subsurface geological features, which is critical for improving seismic hazard assessment in general and in particular in the study area the EBSZ. The integration of the different methodologies has also provided a detailed view on the geometry and nature of the Critical Zone in a highly deformed area and how it is affected by the fault zones.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

*“Science knows no country because knowledge belongs to humanity and is the
torch which illuminates the world.”*
— Louis Pasteur

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

Three different geophysical methods, Multichannel Analysis of Surface Waves (MASW), P- wave tomography, and resistivity, were used to characterize the shallow subsurface features in the one of the most active fault systems in the Iberian Peninsula, the Eastern Betics Shear Zone (EBSZ). An extra effort has been devoted to develop our own workflow approaches for MASW. The common goal of this memoir was to develop a multi-parameter model of the subsurface along a number of active fault zones within a band of deformation that includes the Alhama de Murcia main fault (AMF) and the Carrascoy fault system (CAF). Based on the geophysical (P-wave, S-wave and resistivity) models obtained in the study area, and their combination with surface geology information (trench and geological mapping), the following main conclusions can be highlighted:

- 1) The 2D velocity depth models (S- and P- waves) obtained clearly showed the seismic signature of the fault zones and allowed to identify a number of possible blind faults and fractured/tectonized zones previously not mapped. These elements are new key inputs for the subsequent seismic hazard assessment (SHAs). The seismic signature of fault zones and blind faults are imaged as relatively low-velocity domains with V_s values within the range of 500-1000 m/s and V_p 's on the range of 1300-1700 m/s these have a sensible impact reducing the shear- and bulk-modulus along the fault plane. Areas with high fracture density could be associated with fault zones (damaged zones), which in turn may be related to high strain concentrations. The Carrascoy and La Torrecilla profiles show more fractures than La Salud South and La Salud North profiles. This qualitative difference might be indicative of differences in the deformation scenario and/or the degree of maturation of the fault.

- 2) The indirect geophysical methods employed in this experiment provided measurements of different physical properties of the near surface (V_s , V_p , seismic velocities and, resistivity). These properties are then used for imaging the thickness of the critical zone (CZ – upper boundary of fresh bedrock and the sediments above it) at various scales (meters to tens meters). In the EBSZ, the critical zone (CZ) is characterized low seismic velocities ($V_s < 600$ m/s and $V_p < 1300$ m/s), which is consistent with the expected relatively low resistivity layer of Quaternary alluvial sediments in the La Torrecilla, La Salud North, and La Salud South profiles, and the Unidad Roja (Red Unit) and the Pleistocene-Quaternary alluvial in the Carrascoy profile. The thickness of the CZ in La Salud North profile ranges from 35-45 m and in La Salud South profile within 40-47.5 m. Furthermore, the thickest CZ layer is identified in the La Torrecilla profile with a thickness of *ca.* 40-50 m and the thinnest CZ is located in the Carrascoy profile with a thickness of *ca.* 30-40 m.
- 3) The images obtained (2D physical property models) of the CZ suggest correlations between: the overall CZ thickness; the geographic location and, the subsurface geologic structures. In tectonic active deformation areas, where fault zone and elevation/topography differences coexist, one or both of these factors can perhaps control the thickness of the CZ. Faults could can be responsible for: changes in bedrock elevation due to changes in fault geometry and/or an increase thickness and relevance of the regolith layer. As a result, the CZ layer near the fault zone becomes relatively thicker than locations far from the fault zone. Knowledge, on the specifics of the CZ and fault geometry configuration are critical in providing the structural setting (pathways) for the local hydrology scenario. Note that damage and/or highly fractured zones features potentially higher hydraulic conductivity which can significantly raise pore pressure, reduce effective stresses, decrease seismic (V_p and V_s) velocities, increase attenuation, and amplify the fracturing effect.

8.2 Future work

According to the results of this memoir, further work should focus on obtaining new V_p and V_s models along other faults and fault segments of the Eastern Betic Shear Zone to provide a larger picture of the shallow subsurface structure of this strike-slip system and the thickness of CZ in 3D. To achieve this goal, additional integrated geophysical surveys and borehole data are required. So far, only a few studies have started to apply integrated multi-geophysical approaches to CZ resulting in different imaging depths and resolutions, for example: methods as: seismic techniques, GPR, and ERT [Picozzi et al., 2009; Pilz et al., 2012; 2014; Parsekian et al., 2015].

In addition, future work could address the integration of the geophysical data using more advanced interpretation strategies, e.g., machine learning or joint inversion [Malehmir et al., 2016; Ogaya et al., 2016; Marzán et al., 2021]. With the application of these geophysical methods, coupled with adequate borehole data, further studies are expected to be able to provide a comprehensive 3D image of the distribution of the CZ layer, geological structures, and fluids content inside the CZ.

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APPENDIX 1. PAPER CONFERENCE

Multichannel Analysis of Surface Waves (MASW) to Characterize of Fault Zone in Alhama de Murcia Fault

Near Surface Geoscience (NSG) Conference & Exhibition Online 2020

Multichannel Analysis of Surface Waves (MASW) to Characterize of Fault Zone in Alhama de Murcia Fault

H. Handoyo^{1,2}, J. Alcalde¹, D. Martí³, J.J. Martínez-Díaz⁴, T. Teixidó⁵, R. Carbonell¹

¹ Institute of Earth Sciences Jaume Almera (ICTJA-CSIC), Department of Earth's Structure and Dynamics, Barcelona, Spain

² Teknik Geofisika Institut Teknologi Sumatera, South Lampung, Indonesia

³ Lithica SCCL, Santa Coloma de Farners, Girona, Spain

⁴ Universidad Complutense de Madrid, Madrid, Spain

⁵ Universidad de Granada, Granada, Spain

Summary

The fault structure of the Alhama de Murcia Fault (AMF) has been characterized using the analysis of surface waves identified in shallow high-resolution seismic reflection data. Multichannel analysis of surface waves (MASW) is applied to visualize the 2D Vs wave velocity model and image the geometry of the fault system in the segments of the fault located in the La Salud area. Two approaches have been used to achieve a well-constrained velocity model in the AMF fault zone. Standard seismic reflection processing workflow has been used to clear the seismic data and increase its S/N ratio. The Occam's inversion has been used to invert the digitized surface wave dispersion curves. 1D shear wave velocity-depth profiles were estimated in shot and CDP domains. The result of this study is a 2D velocity-depth crosssection relatively well resolved were obtained by a composite of the 1D velocity-depth functions. These inversion 2D-velocity models can constrain the depth geometry of the fault zone up to 100 m depth penetration. The fault zone is indicated by a relatively low-velocity anomaly by decreasing shear modulus that correlates with the fault's surface expression.

1. Introduction

The Alhama de Murcia Fault (AMF) has been intensively studied because it is one of the most active faults in the Iberian Peninsula. Some research has focused on characterization and determination of the AMF (Ortuño et al., 2012 and Martínez-Díaz et al., 2012), especially from surface and trench studies. However, further research is required to fully understand the characteristics of this strike-slip fault (i.e. orientation, geometry, and configuration) because the geometry of this fault beneath the surface is still unknown. Revealing its subsurface characteristics can help to understand its structure and how it accommodates the deformation, hence aiding in future seismic hazard assessments.

Multichannel analysis surface waves (MASW) is one of the most powerful geophysical methods capable of imaging a variety of features in the shallow subsurface, including zone fault structures (e.g. Ivanov et al., 2006). This study employs MASW in one section of the AMF area in order to obtain 1D2D shear wave velocity-depth models and to further constrain the deep geometry of the AMF fault structure in La Salud area (Figure 1). This work presents the preliminary results of these analyses, and propose the next processing steps to be carried out in the seismic datasets acquired along the AMF area.

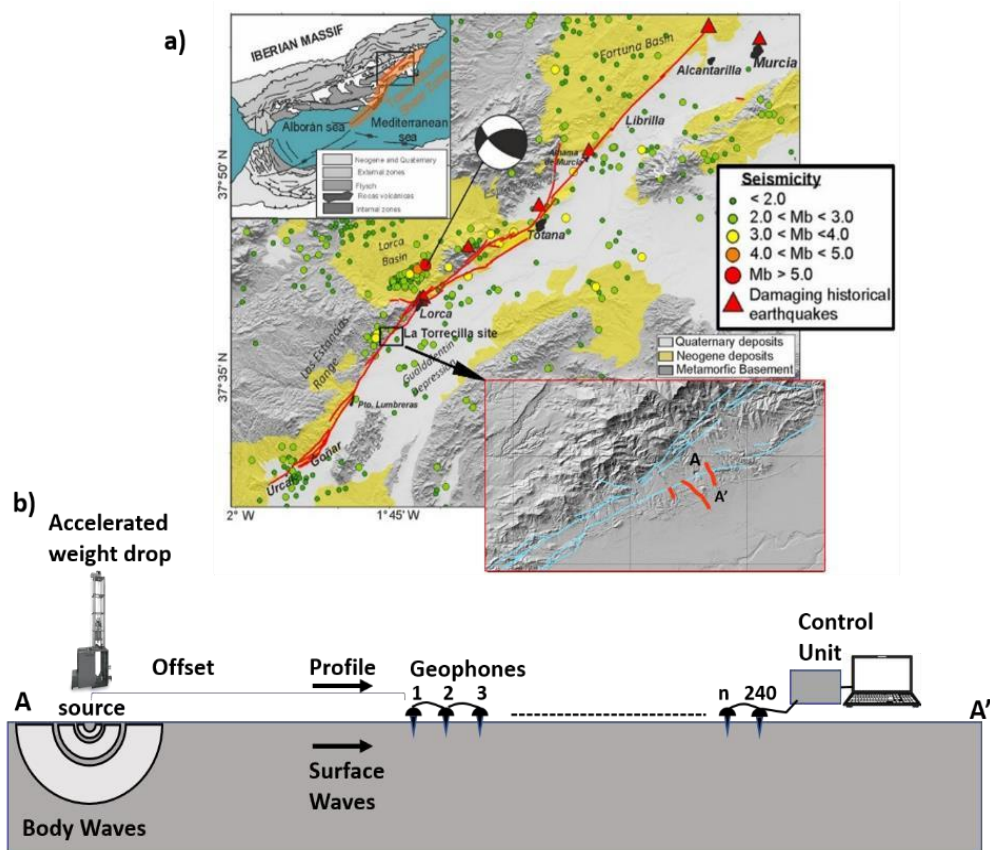


Figure 1 a) Location of the study area in the southeastern Iberian Peninsula, and simplified geology of the area including the recorded seismicity. The main image reveals the trace and distribution of the identified fault traces (in red). The focal mechanism of the Mw 5.2 Lorca earthquake is indicated by the beach-ball. b) The illustration of the MASW methodology across the AMF in seismic line A-A'.

2. Geological Setting

Geological and geometric architecture sediment formation in the study area was controlled by a series of faults with ENE-WSW directions (Fig. 1). These set of faults are considered to be the core of a strike-slip shear fracture system, being the AMF the main structural feature. The shear zone is a nearly 1 km wide deformation zone that contains a set of faults with NW-SE and SW-NE directions. Several instrumental and historical earthquakes have been identified along this deformation structure (Fig. 1). Detailed geology and paleoearthquake studies can be found in Martínez-Díaz et al. 2012 (and references therein). These studies describe the surface geology and how the AMF affected the geomorphological expression in the area.

3. Seismic Data

The seismic reflection data employed in this study were acquired within the framework of the INTERGEO Project. The seismic profile that will be analysed here, A-A' (Fig. 1), is located next to the city of Lorca. The main goal is to image the subsurface structures and their geometry, as well as studying the expression at the depth of the AMF, focusing on architectural relationship between the different fault planes and the relations with the deposition of depressed sediment of the Guadalentín basin.

The acquisition experiment includes a series of transects across different sections of the surface expression of the fault system. This acquisition was carried out using a 240 channels system consisting of 10 GEODE recording units with 24 channels each (Fig.1). This recording system was provided by the GIPP-GFZ Instrumentation Center (Potsdam, Germany). The seismic source used was a 200 kg accelerated weight-drop provided by the Instituto Tecnico Superior at the University of Lisbon, (Lisbon, Portugal). The distance from the seismic source to the first receiver and the shot spacing was set to 6 m. The sample rate was 1 ms and the total recording time was 4 s.

4. Method

The shot records reveal prominent dispersive surface waves (Fig. 2). To increase the S/N ratio, simple and conventional seismic processing was applied at the beginning of the processing flow. It mostly consisted in attenuating the high-frequency signal and amplitude balancing (normalization). This basic processing increased the lateral continuity and extent of the different phases and increased the energy of the S-wave arrivals. Then, the phase velocity-frequency diagram (dispersion curve) was calculated (Figure 2.b). This was obtained by calculating the Fast Fourier Transform (FFT) process of the Tau-P_z transformed shots record. The dispersion curve was then digitized (dispersion curve extraction) to obtain the main phase velocity and frequency of the data. Further analysis were carried out using the dispersion curve estimated by the specific surface wave dispersion module from the Seismic -Unix software package, called *suphasevel* (Cohen and Stockwell, 2010).

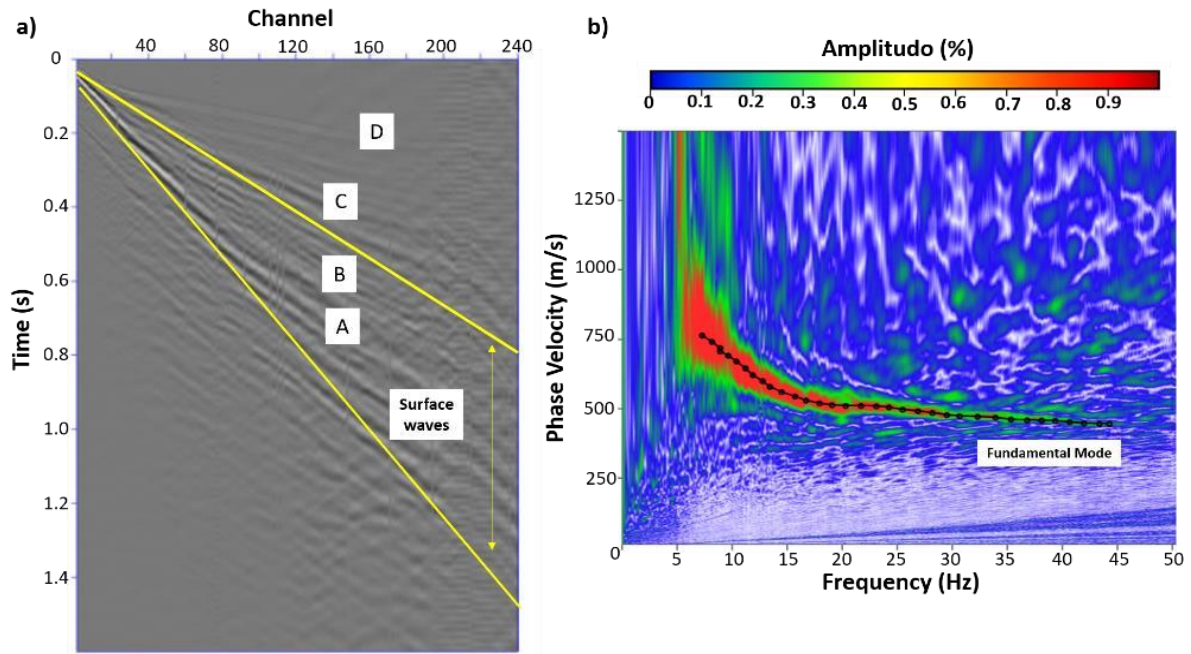


Figure 2 a) Example of the seismic shot record corresponding to the La Salud profile and its dispersion diagram. The labeled phases correspond to: (A) the fundamental mode, (B) the higher modes, (C) the reflection wave, and (D) the refraction wave. b) The right image corresponds to the dispersion diagram of the surface waves. The high amplitudes are indicative of the different phases (frequency and phase velocity).

The frequency-velocity curves obtained from the dispersion curve extraction were then used in an Occam's inversion scheme approach yielding 1D velocity-depth profile (Park et al., 1999). This involves using an inversion scheme for calculating the V_s velocity-depth profile using a repetitive inversion algorithm that requires digital dispersion curve input and a fair value for density and Poisson's ratio (Xia et al., 1999).

5. Results and Discussion

The seismic shot gathers shown in Fig. 2 is an example of the quality and lateral continuity of the ground roll waves imaged in the shot records. In these records, the surface wave energy dominates the seismic data and appears to be quite dispersive. This effect is recognized as a multiple of surface waves and is relatively coherent. The dispersion curve obtained shows the value of the phase velocity with respect to the frequency of the surface wave. The results of the dispersion curves are usually presented as two-dimensional images obtained by cross-plotting the normalized frequencies and phase velocities. The high-energy bands observed display the dispersion characteristics of the recorded surface waves (Fig. 2).

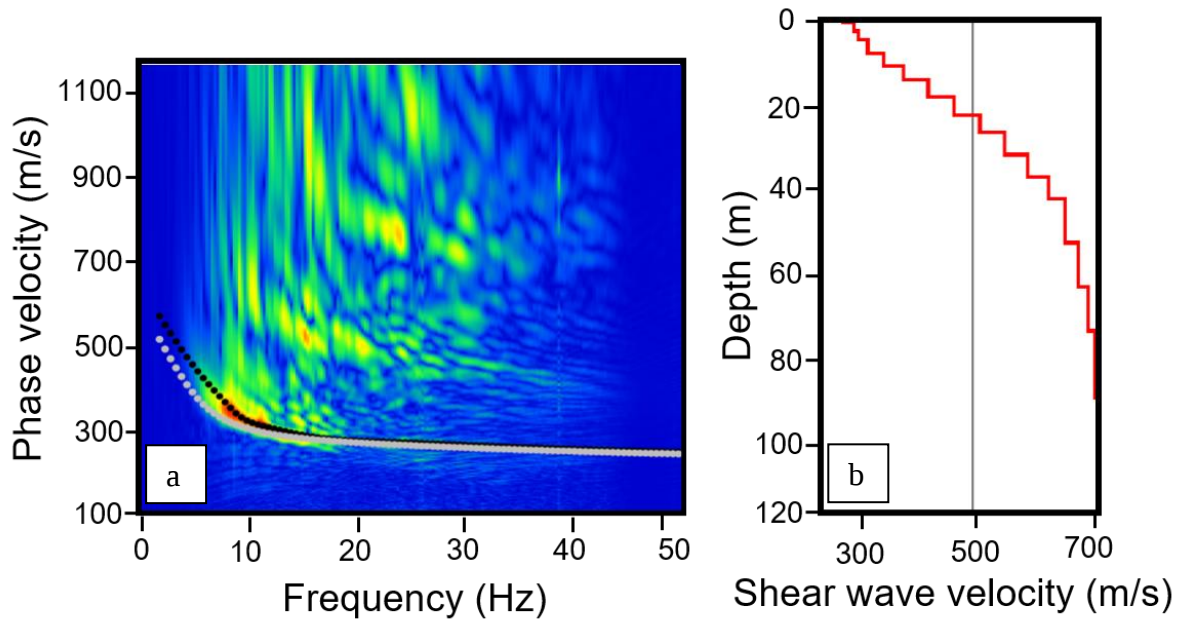


Figure 3 a) Phase vs frequency of the surface waves. The theoretical curve is shown as white dots and, the inversion curve is represented by black dots. b) The velocity-depth model is determined by the inversion scheme.

After the dispersion curves were generated, the maximum spectrum trend of the dispersion curve is digitized in order to extract the best value of frequency and phase velocity (Fig. 3a). Based on the energy content of the recorded surface waves, one or multiple dispersion curves can be extracted from the phase velocity spectra. We used the fundamental mode dispersion characteristics, which are the most commonly used in the inversion schemes (Xia et al., 1999). In this study, the fundamental mode was used in the inversion to obtain the depth-velocity model (Fig. 3b).

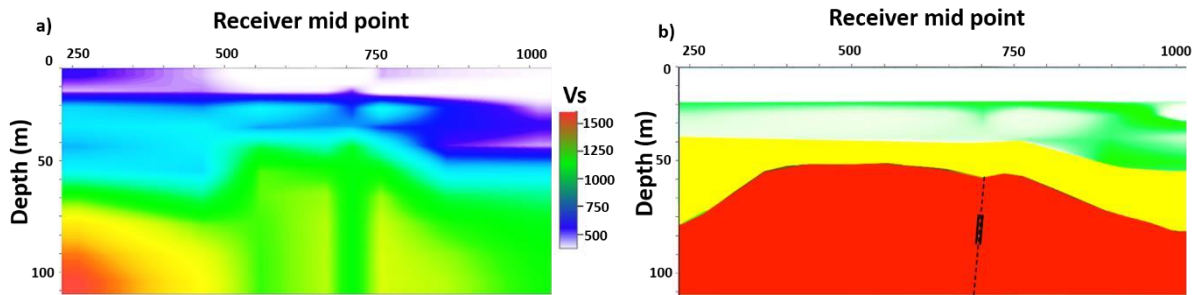


Figure 4 a) Shear-wave velocity model. Composite velocity cross-section obtained by pasting together the 1D velocity-depth profiles obtained by the inversion of the digitized dispersion curves. b) the interpreted geological model. The sedimentary cover in white, green, and yellow, and the location of a steeply dipping feature indicated by the relatively low-velocity anomaly and interpreted as a possible expression of the AMF.

The 2D S-wave velocity model and geological interpretation are shown in Fig.4. The 2D composite Vs section reveals a laterally varying structural model and covered the depth of about 120 m. The shear wave velocity model presents areas of relatively low-velocity values (400-900 m/s) and areas of higher velocity values (1000-1500 m/s) below 50 m (Fig. 4a).

Perhaps one of the most important findings of the study is the steeply dipping low-velocity anomaly at receiver location 700. This relatively thin anomaly has been interpreted as a trace of the AMF fault zone. The geological interpretation from the MASW result is shown in Fig. 4b. The fault zone interpreted as a parallel block of bedrock (red color) that is assumed as a strike-slip fault at depth more than 50 m in around receiver midpoint 700. The other velocity values were interpreted as the sedimentary cover and bedrock (yellow, green, and white color). This low-velocity anomaly is interpreted to represent the location of the fault zone. The low velocities would then be related to fracturing and associated local weathering that would reduce the shear modulus value.

6. Conclusions

The MASW method was used to map the geometry of the AMF strike-slip fault in La Salud area. The preliminary results of the MASW analysis reveal a steeply dipping relatively low-velocity anomaly that can be correlated at the surface with the trace of the AMF. The procedure consisted in digitizing the maximum values in the dispersion curves and using an inversion scheme to obtain 1D velocity depth profiles at different surface locations. These 1D functions were then pasted together by interpolation to obtain a composite 2D velocity model. In this study, the preliminary velocity models reveal the fault zone of the AMF as a remarkable low-velocity anomaly that can be traced down to 50 m depth.

7. Acknowledgements (Optional)

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APPENDIX 2. POSTER CONFERENCE

Near Surface High-Resolution Characterization of the Seismogenic Alhama de Murcia Strike-slip Fault

EGU General Assembly 2021

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Near-Surface High Resolution Characterization of the Seismogenic Alhama de Murcia Strike-slip Fault

Handoyo Handoyo¹, Imma Palomeras², Juan Alcalde¹, Irene de Felipe¹, David Martí³, Julian GarcíaMayordomo⁴, Jose Jesus Martínez-Díaz⁵, Teresa Teixidor⁶, Juan Miguel Insúa-Arevalo⁵, and Ramon Carbonell¹

¹Geosciences Barcelona, (Geo3BCN-CSIC) Spain (handoyo.geophysics@gmail.com)

²University of Salamanca, Salamanca, Spain

³Lithica SCCL, Santa Coloma de Farners, Girona, Spain

⁴Geological and Mining Institute of Spain, Madrid, Spain

⁵Universidad Complutense de Madrid, Madrid, Spain

⁶Universidad de Granada, Granada, Spain

In Spring 2011 (11th of May), the vicinity of Lorca city (Murcia, SE Iberian Peninsula) was hit by two main seismic shocks that reach a maximum magnitude of 5.2 Mw. The earthquake caused serious widespread damage in the city and its surroundings. Similar events have affected the area regularly in the past (for example: on May 6, 1977, 4.2 mg). These events are distributed along a relatively broad band (roughly NE-SW oriented) parallel to the coast, associated to the activation of the Alhama de Murcia Fault (AMF), an oblique-slip (reverse-strike-slip) fault system located in the Eastern Betics Shear Zone. The current study aims to characterize the shallow subsurface across some of the surface outcrop of a few of the main faults that lie within this seismogenic strike-slip fault system. Six normal-incidence seismic reflection profiles were acquired in the area crossing the AMF and the Carrascoy fault, among others). This study focuses on the determination of the shear-wave velocity depth model by applying Multichannel Analysis of Surface Waves (MASW), using the shot records of the seismic reflection profiles. The 1D velocity-depth functions acquired were pasted together to obtain the final 2D velocity models. The hand-picked dispersion curves were inverted using two different approaches to address the consistency of the inversion schemes. The final models reveal relevant differences across the different fault zones, reflecting the heterogeneity and lateral variability that characterizes a complex seismogenic zone, a most probably, diffuse plate boundary.

This research is supported by: Generalitat de Catalunya (AGAUR) grant 2017SGR1022 (GREG); EU (H2020) 871121 (EPOS-SP); EIT-RawMaterials 17024 (SIT4ME), CGL2013-47412-C2-1-P.

Structure of the shallow subsurface across an active strike-slip fault system: The case of the Carrascoy fracture zone, (SE Iberia Peninsula)

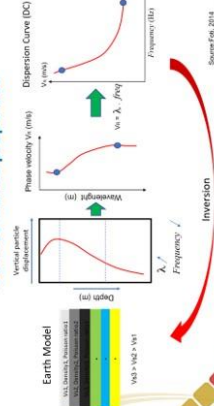
Handoyo^{1,2}, J. Alcalde¹, R. Martín-Banda³, I. Palomeras⁴, I. de Felipe¹, J. García-Mayordomo⁴,
D. Martí⁵, J.J. Martínez-Díaz⁶, T. Teixidó⁷ and R. Carbonell¹



MOTIVATION

- In this contribution, we aim to determine the near-surface structure (up to ~300m depth) across this tectonically meaningful feature by analyzing its seismic expression in the high-resolution seismic dataset.
- Applying the MASW processing and interpretation flow to obtain structural cross-section across the active CF fault, located within the deformation corridor of the EBSZ.

Surface waves properties



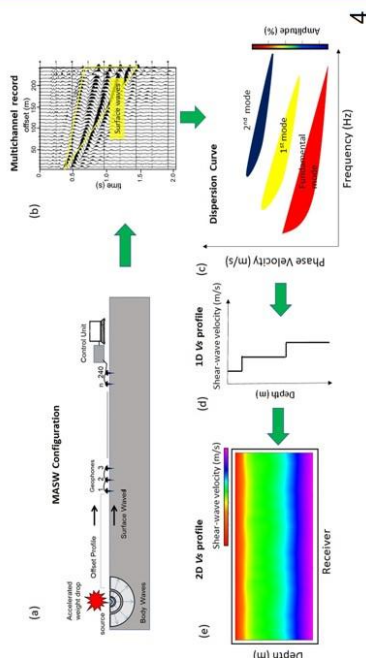
SEISMIC DATA



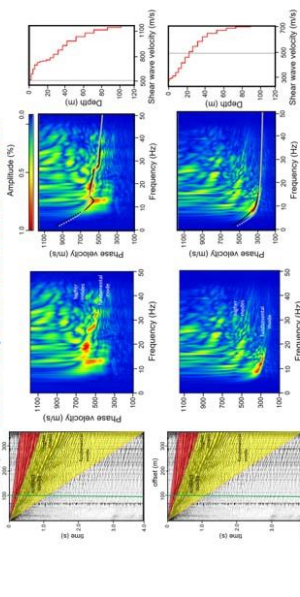
Parameter	Description
Accelerating voltage (kV)	4.0
Current (mA)	3.72
Slit size (mm)	3.72
Total counts	2226.9
Beam length (mm)	5.0
Beam spot (mm)	2.40
Exposure time (s)	1.00
Composite standard intensity	510
Channel speed	4.0
Channel width	4.0
Recording time (s)	4.0
Sample size (mm)	4.0
Sample area (mm ²)	16.0

DATA:
[Access through](#)
[SciDARE \(self-ref. et al.,](#)
[2020 doi: 10.5194/essd-2020-](#)
[2000 doi:](#)
[10.5194/essd-2020-2000](#)

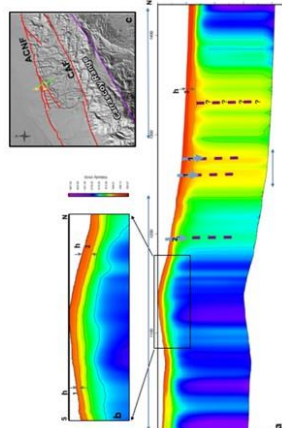
The MASW Workflow



Result: Dispersion Curve and 1D Inversion



Result: 2D Vs profile and fault zone interpretation



Discussion: Vp & Vs Comparison

- The generalized geological model of CF fault (modified from Martin-Banda, R. et al., 2016).
- The 2D P-wave velocity profile across CF and its fault interpretation. The Vp 2D profile was obtained from other research in same location in the MASW profile. Its Vp 2D profile was generated by using seismic tomography method.
- The Field site of the MASW 2D S-wave velocity profile and fault interpretation.

The P-wave and S-wave velocity profile reveals to nearly vertical low velocity anomalies (two arrows) that appear to correlate with the surface outcrops of the Algezares-Casas Nuevas faults and its fault branches. The other low velocity anomalies are perhaps the responses of local fault zones.

Conclusion

1. The 5-wave high-resolution near-surface study based on MASW was conducted in the E2B2 area, characterize the shallow subsurface across the Contreras fault (CF) in the E2B2 area. In this study, the 5-wave velocity model was constrained down to 300 m depth.
2. The 5-wave velocity model reveals velocity anomalies and several layers/fault zone.
3. This is the most well developed fracture zone which shows the lowest velocity values. This low velocity anomaly most probably marks the halo/monocline of altered, fractured (relatively unconsolidated) areas associated to the fracture (Algarres-Casas Novas fault).

APPENDIX 3. PAPER CONFERENCE

Multichannel Analysis of Surface Wave (MASW) across the Alhama de Murcia Fault Zone: The Case of Fault Structure of La Salud Area

X Congreso Geológico de España, July 5-7, 2021, Vitoria-Gasteiz, Spain

Multichannel Surface-Wave-Analysis (MASW) across the Alhama de Murcia Fault Zone

Caracterización de la Falla de Alhama de Murcia mediante MASW

Handoyo^{1,2}, J. Alcalde¹, D. Martí³, J.J. Martínez-Díaz⁴, T. Teixidó⁵ and R. Carbonell¹

- 1 Institute of Earth Sciences Jaume Almera (ICTJA – CSIC), Department of Earth's Structure and Dynamics, C/Lluís Solé i Sabarís s/n, 08028, Barcelona, Spain, handoyo.geoph@tg.itera.ac.id; jalcalde@ictja.csic.es, ramon.carbonell@csic.es
- 2 Teknik Geofisika, Institut Teknologi Sumatera, Jalan Terusan Ryacudu Kecamatan Jati Agung, Lampung Selatan, Indonesia
- 3 Lithica SCCL, Santa Coloma de Farners 17430, Girona, Spain. dmarti@lithica.net
- 4 Universidad Complutense de Madrid, Avda. de Séneca, 2 Ciudad Universitaria 28040, Madrid Spain. jmdiaz@geo.ucm.es
- 5 Universidad de Granada, Calle La Paz 18, 52005, Granada, Spain. tteixido@ugr.es

Abstract: The deep structure of the Alhama de Murcia Fault (AMF) is characterized by means of the analysis of surface waves identified in shallow high-resolution seismic reflection data. Multichannel analysis of surface waves (MASW) is used to unravel the 2-D S-wave velocity model and image the depth geometry of the fault system. The study area includes segments of the fault located in La Salud area. Two approaches have been used to achieve a well constrained velocity model in the AMF fault zone. Conventional seismic reflection processing work flow has been used to clean the seismic data and increase its S/N ratio. Occam's approach has been used to invert the digitized surface wave dispersion curves. 1D shear wave velocity-depth profiles were estimated in shot and CDP domains. Relatively well resolved 2D velocity-depth models were obtained by composite of the 1D Velocity-depth functions. These composite 2D-velocity models are able to constrain the depth geometry of the fault zone up to 100 m depth. The fault zone is indicated by a relatively broad low velocity anomaly that correlates with the fault's surface expression.

Keywords: Surface wave dispersion, strike-slip fault, seismic inversion, Alhama de Murcia Fault, MASW

Resumen: La estructura profunda de la falla de Alhama de Murcia (AMF) ha sido caracterizada mediante el análisis de ondas superficiales identificados en datos de reflexión sísmica superficial de alta resolución. El análisis multicanal de ondas de superficie (MASW) es usado para desentrañar un modelo 2D de Vs y para obtener imágenes de la geometría del sistema de fallas en profundidad. El área de estudio incluye segmentos de la AMF ubicados en el área de La Salud. Se han utilizado dos enfoques para lograr modelos de velocidad bien restringidos de la zona de falla. Por un lado, se han limpiado los datos utilizando un flujo de procesamiento convencional diseñado para aumentar su ratio de señal/ruido. Por el otro, se ha usado el enfoque de Occam para invertir las curvas de dispersión de ondas de superficie digitalizadas. Los perfiles 1D de profundidad de las Vs fueron estimados en los dominios de disparo y de CDP. Se obtuvieron modelos de velocidad-profundidad 2D relativamente bien resueltos mediante la interpolación de las funciones de velocidad-profundidad 1D. Estos modelos de velocidad 2D ayudan a restringir en profundidad la geometría de la zona de falla hasta los 100 m que se caracteriza por una anomalía de baja velocidad relativamente amplia que se correlaciona en la superficie con la expresión de la falla.

Palabras Clave: Dispersión ondas superficiales, falla de salto en dirección, inversión de datos sísmicos, Falla de Alhama de Murcia, MASW

INTRODUCTION

In 2011, a 5.2 Mw earthquake took place in the vicinity of the city of Lorca, Spain. The earthquake produced remarkable damage including nine casualties, over four hundred injured and significant material damage in the area. The earthquake's hypocenter location and focal mechanism were correlated with the activation of the Alhama de Murcia Fault (AMF). This is one of the main faults of a well-known strike-slip fracture system which is one of the most active within the main Iberian Peninsula (Martínez-Díaz et al., 2012). The AMF is a strike-slip shear zone with reverse component that crosses the eastern Betic cordillera with a NE-SW direction and is one of the largest faults of the Eastern Betics Shear Zone (Silva et al., 1993).

Several studies have focused on the characterization and determination of the AMF attributes, such as its seismic potential (Ortuño et al., 2012; Martínez-Díaz et al., 2012), mainly from surface and trench studies. However, the understanding of fault properties (orientation, geometry, and configuration) requires further research as the deep geometry is not well resolved. Addressing these targets can provide an understanding of the detailed structure, the distribution of its deformation and help in the assessment of seismic hazard.

Multichannel analysis of surface waves (MASW) is able to constrain a relatively wide range of subsurface features, for example delineate the shallow structure of fault zones (Ivanov et al., 2006). This approach is able to infer the 1D Vs structure of subsurface materials (Bergamo and Socco, 2016) and delineate underground structures such as voids or tunnels (Peterie and Miller, 2015). The study presented here employs MASW in one section of the AMF. The main objective is to obtain a 2D shear wave-velocity depth models and to

better constrain the deep geometry of the AMF fault structure in the La Salud area.

GEOLOGICAL SETTING

The geological architecture and the geometry of sedimentary formations in the study area are controlled by a set of faults with ENE-WSW directions (Fig. 1). These set of faults are considered to be the backbone of a strike-slip shear (fracture)-system. The Alhama de Murcia Fault System (AMF) can be considered, perhaps the main structural feature. The shear zone is a nearly 1 km wide zone of deformation that includes a set of faults with NW-SE and SW-NE directions. Along this deformation structure a number of instrumental and historical earthquakes have been identified (Fig. 1). Detailed geology and paleogeomorphologic studies can be found in Martínez-Díaz et al. 2012; and references therein). These studies describe the surface geology and, geomorphology of the main fault (AMF).

SEISMIC REFLECTION DATA

A seismic reflection controlled source data acquisition experiment was carried out within the framework of the INTERGEO project. The seismic profiles (Fig. 1) were located in the vicinity of the city of Lorca. The main idea was to address the subsurface structure, the shape, and the architecture depth expression of the AMF, focusing on the architectural relationship at depth between the different fault planes and the relationship with the sedimentary filling of the Guadalentín depression. Therefore, the data acquisition experiment included a series of transects across different surface expressions of the fault system. It was acquired using 240 channel system which consisted in 10 GEODE recording units with 24 channels each. The recording system was provided by the GIPP-GFZ instrumentation center. (Potsdam, Germany) The source was a 200 kg accelerated weight drop provided by the Instituto Superior Técnico in Lisbon University, (Lisbon, Portugal). The

distance from the seismic source to first receiver and the shot spacing were both set to 6 m. The sample rate was set to 1 ms and the total recording time was 4 s.

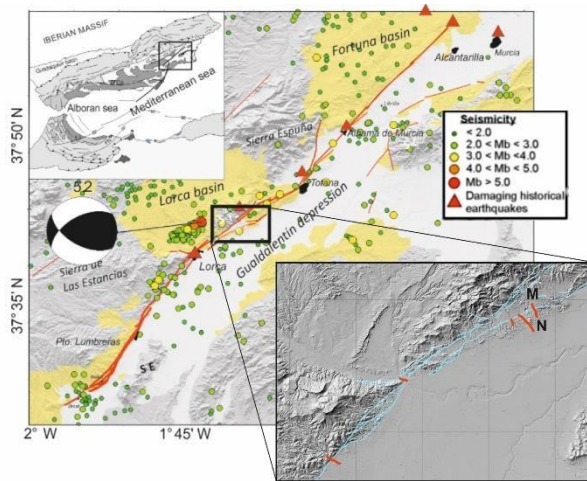


FIGURE 1. Location of the study area. The top inset indicates the overall location of the deformation zone in southeastern Iberian Peninsula. It also illustrates a simplified geology of the area. The main image reveals the trace and distribution of the identified fault traces. The coloured dots correspond to the recorded seismicity, instrumental and historical earthquakes with M_w larger than 1. The focal mechanism of the M_w 5.2 Lorca earthquake is indicated by the beach-ball. The bottom inset indicates the location and trace of the high resolution, normal incidence seismic reflection profiles acquired across the AMF. The M-N transect is used in this study.

The shot records reveal prominent dispersive surface waves (Fig. 2). In order to increase the S/N ratio simple and conventional seismic processing was carried out. It mostly consisted in attenuating the high frequency and amplitude balancing. This simple and basic processing increased the lateral continuity and extent of the different phases and increased the energy of the S-wave arrivals.

Then the frequency-phase velocity diagrams also known as the wave-dispersion diagrams were obtained. These were determined by calculating the FFT of the Tau-P transformed shot gathers. The dispersion curves were then digitized.

These frequency-velocity curves were then used in an Occam inversion scheme approach that resulted in 1D velocity-depth profiles (Park et al., 1999).

This process was applied to data from La Salud transect where the fault zone has been mapped at surface (Fig. 1). The V_s -depth profiles were then joined together to build a composite 2D velocity model of the area. The process was repeated but in this case the wave-dispersion diagrams were calculated for the CDP sorted data. Further comparisons were carried out by using the dispersion diagrams estimated by the specific surface wave dispersion module from the Seismic Unix software: the *suphasevel* (Cohen and Stockwell, 2010).

The inversion scheme to compute the V_s velocity-depth profiles is an iterative inversion algorithm that requires as inputs the digitized dispersion curve and reasonable values for densities and Poisson's ratio (Xia et al., 1999). A comparison between available commercial and academic software packages to estimate V_s profiles has also been considered in this study.

RESULTS AND DISCUSSION

The shot gather (Fig. 2) is an example to illustrate the quality and lateral continuity of the ground roll imaged within the shot records. In these records, the surface wave energy dominates the seismic data and appear moderately dispersive. This effect is recognizable as multiples from the surface waves and it is relatively coherent.

The maximum of the dispersion diagram was then digitized and a dispersion curve was extracted. The dispersion curve shows the value of phase velocity against frequency of the surface waves (Fig. 2).

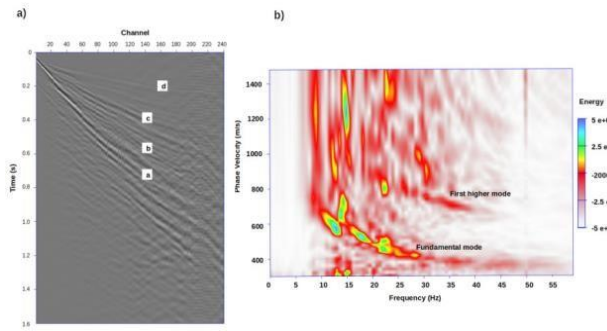


FIGURE 2. Example of seismic shot record corresponding the Salud profile and its dispersion diagram. The labelled phases correspond to: (a) the fundamental mode of surface wave, (b) the higher modes of surface wave, (c) the reflection wave, and (d) the refraction wave. The right image corresponds to the dispersion diagram of the surface waves. The high amplitudes are indicative of the different phases (frequency and phase-velocity).

The dispersion curve generated from each shot record was assigned a location corresponding to the receiver midpoint of its receiver spread. The fundamental mode and first higher mode appear moderately clear in the resulting dispersion curve images (Fig. 2).

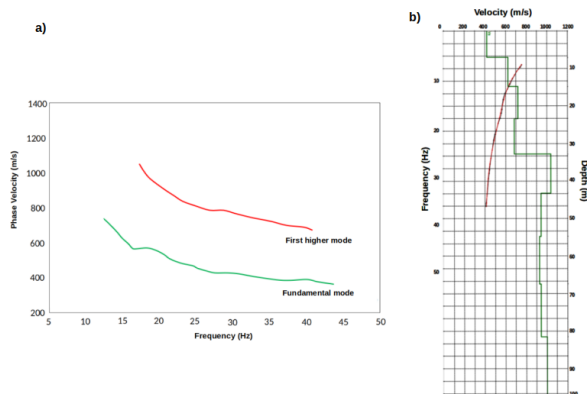


FIGURE 3. The extracted dispersion curves of the different modes calculated for every station (left). The fundamental mode is shown as a green line and, the first higher mode is represented by red line. The velocity-depth functions determined by the inversion scheme are shown in the right diagram.

The results of the dispersion curves are usually presented as two-dimensional images obtained by cross plotting the normalized frequencies and phase velocities. The high-energy bands

observed display the dispersion characteristics of the recorded surface waves (Fig. 2).

After the dispersion curves were generated, the maximum spectrum trend of the dispersion curve is digitized in order to extract the best value of frequency and phase velocity. Base on the energy content of the recorded surface waves, one or multiple dispersion curves can be extracted from the phase velocity spectra. In Fig. 2, the fundamental mode is clearly identified and easy to pick. The first higher mode does not appear as clear but still it can be identified based on its similar trend compared to the fundamental mode dispersion curve. The fundamental mode dispersion characteristics are, usually, the critical and most commonly used in the inversion scheme (Xia et al., 1999). In this study, the fundamental mode and first higher mode were used in the inversion step.

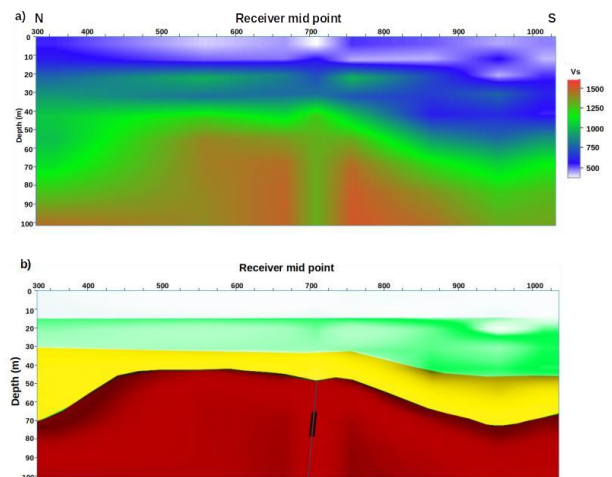


FIGURE 4. Top Shear-wave velocity field. Composite velocity crosssection obtained by pasting together the 1D velocity-depth profiles obtained by the inversion of the digitized dispersion curves. Bottom, interpreted geological model. The sedimentary cover in green and yellow, and the location of a steeply dipping feature indicated by the relatively low velocity anomaly and interpreted as the possible location of the ALMF.

The preliminary 2D S-wave velocity model is a composite of the 1D velocity-

depth profiles obtained by inversion of the dispersion curve (Fig. 4). The 2D inversion covered the depth of 100 m and receiver midpoint number from 300 to 1100. The 2D composite V_s section reveals a laterally varying structural model. The shear wave velocity model presents areas of relatively low velocity values (400-900 m/s) and areas of higher velocity values (1000-1500 m/s) at depths below 50 m.

Perhaps one of the most important findings of the study is the steeply dipping low velocity anomaly at receiver location 700. This relatively thin anomaly has been interpreted as the trace of the AMF fault zone (Fig 4). The geological interpretation from the MASW result is shown in Fig. 4b. Based on the 2D V_s section, the main achieved goal is the identification of the AMF. The fault zone is interpreted as a parallel block of bedrock (red color) that has been identified as a strike-slip fault below receiver midpoint 700 at 50 m depth. The strike direction of the fault zone is approximately southwest to northeast (SW-NE). The other velocity values were interpreted as the sedimentary cover and bedrock (yellow, green and white color).

Similar results were obtained when using the CMP gathers to obtain the dispersion curves, but the analysis of this dataset is out of the scope of this work. In any case, and perhaps, the most important finding of the study is the interpreted fault zone of AMF at depth. According to our results (Fig. 4a) the steeply dipping lower velocity anomaly (green color) below receiver midpoint 700, extends down to depths larger than 50 m. It appears to be almost a vertical structure going across and/or splitting the relatively high velocity (red) rock into two sections. This low velocity anomaly is interpreted to represent the location of the fault zone. The low velocities would then be related to fracturing and associated local weathering that would reduce the shear modulus value.

CONCLUSION

The MASW method was used to map the geometry of the AMF strike slip fault in La Salud area. The preliminary results of the MASW analysis reveal a steeply dipping relatively low velocity anomaly that can be correlated at surface with the trace of the AMF. The procedure consists on obtaining the dispersion curves by digitizing the image of the maximum value by the dispersion analysis and using an inversion scheme to obtain 1D velocity depth profiles at different surface locations. These 1D functions are then pasted together by interpolation to obtain a composite 2D velocity model. In this study, the preliminary velocity models reveal the fault zone of the AMF as a remarkable low velocity anomaly that can be traced down to 50 m depth.

ACKNOWLEDGMENTS

We would thank for the data permission to project of InterGEO (CGL2013-47412-C2-1-P) ICTJA-CSIC. The Ministry of Education and Culture of the Republic of Indonesia is thanked for main author's PhD scholarship. JA is funded by MICINN (IJC2018-026335-I). We thank the GIPP-GFZ, (Germany) and Lisbon University (Portugal) for the instrumentation provided.

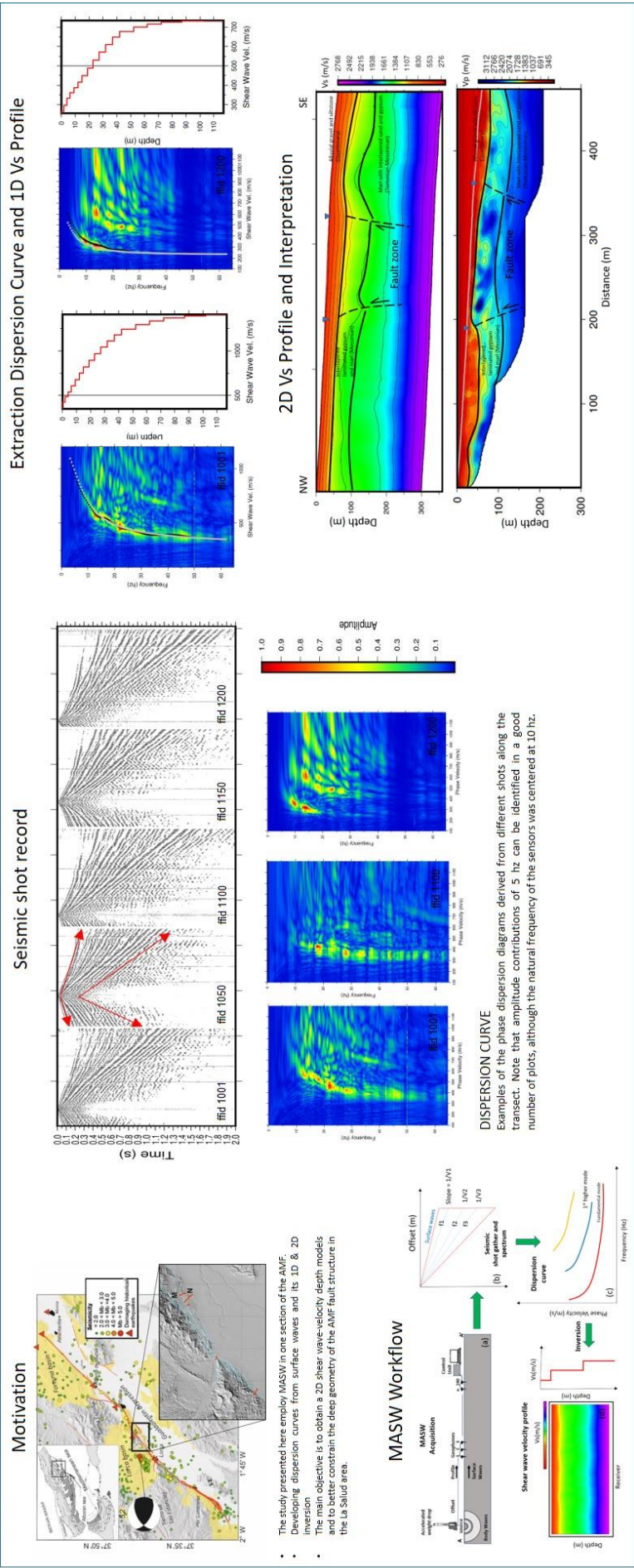
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Multichannel Analysis of Surface Wave (MASW) across the Alhama de Murcia Fault Zone: The Case of Fault Structure of La Salud Area

Handoyo^{1,2}, J. Alcalde¹, R. Martín-Banda³, I. Palomeras⁴, I. de Felipe¹, J. García-Mayordomo⁴, D. Martí⁵, J.J. Martínez-Díaz⁶, T. Teixidó⁷ and R. Carbonell¹



APPENDIX 4. POSTER CONFERENCE

Integrated vision of the shallow subsurface in active deformation zone (Lorca, SE Iberian Peninsula)

International Symposium on Deep Earth Exploration and Practices. Nanjing, China 26 to 31 November 2021



GEO3BCN

Integrated vision of the shallow subsurface in active deformation zone (Lorca, SE Iberian Peninsula)



LITHICA

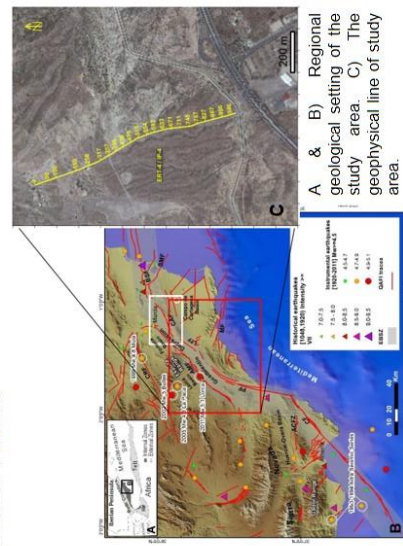
Handoyo^{1,2}, J. Alcalde¹, R. Martín-Banda³, I. Palomeras⁴, I. de Felipe¹, J. García-Mayordomo⁴, D. Martí⁵, J.J. Martínez-Díaz⁶, T. Teixidó⁷ and R. Carbonell¹



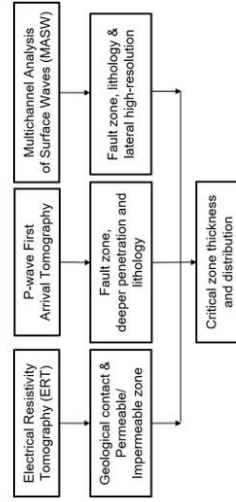
INTRODUCTION

- The Critical Zone (CZ) defines the outermost surface layer of the Earth, where the atmosphere, meteoric water, biota, soil and bedrock interact (Brantley et al., 2007).
- A major component of the CZ is the regolith. Regolith is a layer of rock and soil below the surface where the production and accumulation of soil layers occurs, circulation of groundwater aquifers, and controlling groundwater flow in rock layers and that supports important ecosystems [Field et al., 2015; St Clair et al., 2015; Banwart et al., 2019].
- In this study, we investigated the geometry fault zone and distribution of CZ using geophysical methods (i.e. seismic survey and electrical resistivity tomography ERT) in the Eastern Betics Shear Zone (EBSZ), Spain.

STUDY AREA

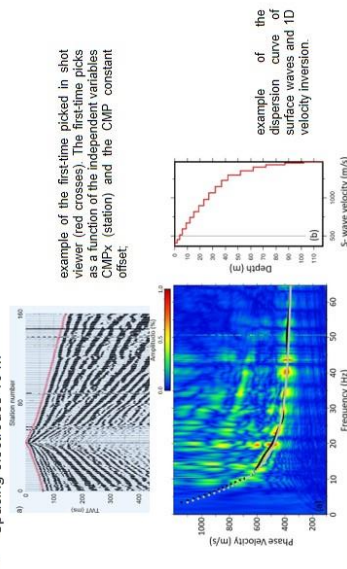


METHODS



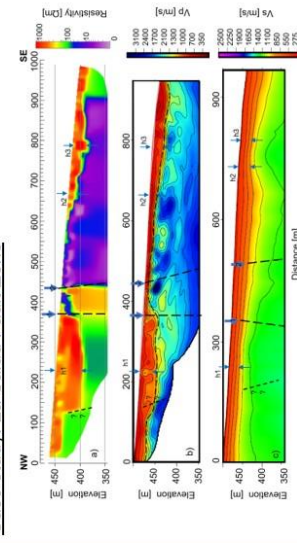
The seismic & ERT data acquisition consisted on:

- a 240-channel system built up by connecting 10 GEODE recording units with 24 channels each,
- The seismic source used was a 200 kg accelerated weight-drop
- The sample rate was 1 ms and the total recording time was 4 s.
- Geophone natural frequency of 10 Hz.
- Spacing electrodes 10 m



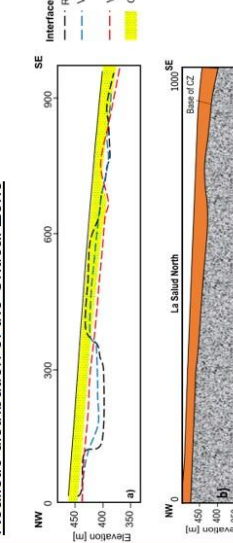
RESULTS

Case study: La Salud Fault Zone



Geophysical imaging of La Salud North site along ~1000 m NW-SE with the interpretation proposed and details with the topography profile. a) the resistivity profile, b) the Vp profile from with the gray line is the topography contour, and c) the Vs profile from MASW

Realistic distribution of the Critical Zone



a) The Geophysical integration imaging of La Salud North site along ~1000 m NW-SE. b) the critical zone distribution & thickness.

APPENDIX 5. SCRIPT OF THE MASW

5.1 Gets information for the headers of the SU formatted files (Seismic Un*x)

hdrvlsu-00.sh

```
=====
#!/bin/zsh
# X11 Display Shots
# Authors: RC
#set -x
## Set input/output file names and data parameters
# =====
# Name of the scritp
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
#echo " ====="
#echo "   Folder Path-> $pth "
#echo " JOB filename -> $JOB "
#echo " ====="
# =====
if [ ! $1 ] ; then
    echo " $JOB Get essential information from trace header values "
    echo "       of su formatted files. "
    echo "       Copies the 6mic gather to the TMP folder to work "
    echo "       output->  dt d1 f1 d2 f2 n1 n2 xmx zmx amx amn nyq "
    echo " "
    echo " Usage: "
    echo "   $JOB flnm "
    echo "       flnm "
    echo " "
    echo "   On output "
    echo "       flnm is also copied to $TMP "
    echo " "
    echo " echoes: dt d1 f1 d2 f2 n1 n2 xmx zmx amx amn nyq ffomn offmx "
    echo "   dt    -> sample rate in ms (eg. 4) "
    echo "   d1    -> sample rate in fast direction (eg time 0.004) "
    echo "   f1    -> starting point for fast axis (time or depth 6mic) "
    echo "   d2    -> sample rate in the slow direction (eg. X axis) "
    echo "   f2    -> starting point for the slow axis (eg. X axis) "
    echo "   n1    -> number of samples in the fast direction "
    echo "   n2    -> number of samples in the slow direction "
    echo "   xmx   -> length of slow axis f2+(ntr-1)*d2 "
    echo "   zmx   -> length of fast axis f1+(ns-1)*d1 (s) "
    echo "   amx   -> Maximum value of Amplitude "
    echo "   amn   -> Minimum value of the Amplitude "
    echo "   nyq   -> Nyquist frequency 1./4*d1 (eg. 125) "
    echo "   offmn -> Minimum offset if not set 0 "
    echo "   offmx -> Maximum offset if not set 0 "
    echo " "
else
    if [[ ! (-e $TMP/$1.su) ]] ; then
        suop op=avg < $1.su > $TMP/$1.su
    fi
fi
```

```

sugethw < $TMP/$1.su key=dt,d1,d2,f1,f2,delrt,ns output=geom | gawk
'END{d1=$2; d2=$3; f1=$4; if ($2==0) d1=($1./1000000.);
if($3==0) d2=1.0; if (($4==0) && ($6!=0)) f1=$6/1000.; xmx=$5+d2*(NR-
1); zmx=f1+d1*($7-1);
printf("%f %f %f %f %f %i %i %f %f
%f\n", $1,d1,f1,d2,$5,$7,NR,xmx,zmx,1./(4.*d1))}' | read dt d1 f1
d2 f2 n1 n2 xmx zmx
sugethw < $TMP/$1.su key=offset output=geom | gmt gmtinfo -C | read
offmn offmx
sumax < $TMP/$1.su output=ascii mode=maxmin outpar=$TMP/$1-amxmn.asc
gawk '{printf("%f %f", $1,$2)}' $TMP/$1-amxmn.asc | read amx amn
echo "$dt $d1 $f1 $d2 $f2 $n1 $n2 $xmx $zmx $amx $amn $nyq $offmn
$offmx"
fi
=====

```

5.2 Tranforms formats handles a variety of formats "form-&-to" SU, grd, USP, bin

transformat-00.sh

```

=====
#!/bin/zsh
# X11 Display Shots
# Authors: RC
#set -x
## Set input/output file names and data parameters
# =====
# Name of the scrip
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
#echo " ====="
#echo " Folder Path-> $pth "
#echo " JOB filename -> $JOB "
#echo " ====="
# =====
if [ ! $1 ] ; then
echo " $JOB Get essential information from trace header values "
echo " of su formatted files. "
echo " Copies the 6mic gather to the TMP folder to work "
echo " output-> dt d1 f1 d2 f2 n1 n2 xmx zmx amx amn nyq "
echo " "
echo " Usage: "
echo " $JOB flnm "
echo " flnm v-1 "
echo " "
echo " On output "
echo " flnm is also copied to $TMP "
echo " "
echo " echoes: dt d1 f1 d2 f2 n1 n2 xmx zmx amx amn nyq fformn offmx "
echo " dt -> sample rate in ms (eg. 4) "
echo " d1 -> sample rate in fast direction (eg time 0.004) "
echo " f1 -> starting point for fast axis (time or depth 6mic) "
echo " d2 -> sample rate in the slow direction (eg. X axis) "
echo " f2 -> starting point for the slow axis (eg. X axis) "
echo " n1 -> number of samples in the fast direction "
echo " n2 -> number of samples in the slow direction "
echo " xmx -> length of slow axis f2+(ntr-1)*d2 "
echo " zmx -> length of fast axis f1+(ns-1)*d1 (s) "

```

```

echo "      amx      -> Maximum value of Amplitude                                "
echo "      amn      -> Minimum value of the Amplitude                            "
echo "      ngy      -> Nyquist frequency 1./4*d1   (eg. 125)                       "
echo "      offmn     -> Minimum offset if not set 0                                "
echo "      offmx     -> Maximum offset if not set 0                                "
echo "                                                                                   "
else
    if [[ ! (-e $TMP/$1.su) ]] ; then
        suop op=avg < $1.su > $TMP/$1.su
    fi
    sugethw < $TMP/$1.su key=dt,d1,d2,f1,f2,delrt,ns output=geom | gawk
    'END{d1=$2; d2=$3; f1=$4; if ($2==0) d1=($1./1000000.);
    if ($3==0) d2=1.0; if (($4==0) && ($6!=0)) f1=$6/1000.;
    xmx=$5+d2*(NR-1); zmx=f1+d1*($7-1);
    printf("%f %f %f %f %f %i %i %f %f
    %f\n",$1,d1,f1,d2,$5,$7,NR,xmx,zmx,1./(4.*d1))}' | read dt d1 f1 d2 f2
    n1 n2 xmx zmx
    sugethw < $TMP/$1.su key=offset output=geom | gmt gmtinfo -C | read
    offmn offmx
    sumax < $TMP/$1.su output=ascii mode=maxmin outpar=$TMP/$1-amxmn.asc
    gawk '{printf("%f %f",$1,$2)}' $TMP/$1-amxmn.asc | read amx amn
    echo "$dt $d1 $f1 $d2 $f2 $n1 $n2 $xmx $zmx $amx $amn $nyq $offmn
    $offmx"
fi
=====

```

5.3 Normalizes a panel/shot gather

pnlnorm.ssh

```

=====
#!/bin/zsh
# Panel norm
# Authors: RC
# NOTE: Comment lines preceeding user input start with  ##
# =====
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
echo " ====="
echo " JOB filename -> $JOB "
echo " ====="
#set -x
## Set input/output file names and data parameters
if [ ! $1 ] ; then
    echo " $JOB Ensemble Processing subshell                                "
    echo "                               normalize entire panel                    "
    echo "                               "                                           "
    echo " Usage:                               "
    echo "   $JOB mode fc scl file-in file-out   "
    echo "                               "                                           "
    echo "                               mode -> abs, max, min, rms   v-1 "
    echo "                               scl      scaling factor      v-2 "
    echo "                               file-in  input file-name     v-3 "
    echo "                               file-in  output file-name    v-4 "
    echo "                               "                                           "
else
    unlink $TMP6/pnscl.asc
    sugethw < $3.su key=dt,d1 output=geom | gawk 'END{printf("%i %f
    \n",$1,$2)}' | read dt d1
    sumax mode=$1 < $3.su outpar=$TMP6/pnscl.asc

```

```

gawk -v val=$2 '{printf("%5.25f\n",val*$1)}' $TMP6/pnscl.asc | read r0
if (( ! $dt )) ; then
    sushw key=dt a=1000 < $3.su | sugain norm=$r0 > $4.su
else
    sugain norm=$r0 < $3.su > $4.su
fi
echo " $JOB: Panel norm factor: $r0"
echo " $JOB: New max. min."
sumax mode=maxmin < $4.su
fi
=====

```

5.4 Computes phase velocity from SU formatted shot gathers and needs correct offsets in headers

rcphsVX-00.sh

```

=====
#!/bin/zsh
# =====
# Name of the script
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
echo " ====="
echo " JOB filename -> $JOB "
echo " ====="
# =====
if [ ! $1 ] ; then
    echo " $JOB Computes the Phase Velocity diagram to estimate "
    echo "         the Surface wave dispersion "
    echo "         It uses the suphasevel program "
    echo " "
    echo " Usage: "
    echo " "
    echo " $JOB dt-flnm np fmx vn vx "
    echo " "
    echo "         dt-flnm         Data file name             v-1 "
    echo "         np              number of ray parameters    v-2 "
    echo "         fmx             Maximum frequency (< Nyquist) v-3 "
    echo "         vn              Minimum phase velocity (m/s) v-4 "
    echo "         vx              Maximum phase velocity (m/s) v-5 "
    echo " "
    echo " The output filename is dt-flnm-PDSW.grd "
    echo " note it is a grd file located in $PRJ "
    echo " There is also a dt-flnm-phsV-01.bin in $TMP "
    echo " "
else
    vn=$4 vx=$5

    dv=$(echo "scale=5; ($vx-$vn)/($2-1)" | bc -l)
    slwn=$(echo "scale=5; 1./$vx" | bc -l)
    slwx=$(echo "scale=5; 1./$vn" | bc -l)
    echo " $JOB # Check Slownes/Phase velocity Velocity vn: $vn (m/s) vx: $vx "
    echo " (m/s), slwn: $slwn (s/m) slwx: $slwx (s/m) dv=$dv s/m"
    hdrvlsu-00.sh $1 | read dt d1 f1 d2 f2 n1 n2 xmx zmx amx amn nyq0 offn
    offx
    echo " dt: $dt, n1: $n1, nyq: $nyq0"
    cd $TMP

```

```

    suphasevel < $TMP/$1.su fv=$vn nv=$2 dv=$dv fmax=$3 | suamp mode=amp >
$TMP/$1-phsV-01.su
    sugethw < $TMP/$1-phsV-01.su key=ns,d1,f1,d2,f2 output=geom | gawk
'END{printf("%i %f %f %f %f %i\n",$1,$2,$3,$4,$5,NR)}' | read np1 dp1 fp1 dp2
fp2 np2
    nf=$(echo "scale=0; ($3/$dp1-1)" | bc -l)
    nyq=$(echo "scale=0; $nf*$dp1" | bc -l)
    dd2=$(echo "scale=0; $dp2*1000" | bc -l)
    echo " $JOB: Parameter Check-> n1: $np1 d1: $dp1 d2: $dp2 f2: $fp2 nyq:
$nyq - $nyq0"
    suwind itmax=$nf < $TMP/$1-phsV-01.su > $TMP/$1-phsV-02.su
    pnlnrm.ssh max 1 $TMP/$1-phsV-02 $TMP/$1-phsV-00
# == Loop to choose the CMP crooked line for the CMP generation and stack
fi
=====

```

5.5 Performs the MASW including displays

fldrMASW00.sh

```

=====
#!/bin/zsh
# =====
# Name of the scrip
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
echo " ====="
echo " JOB filename -> $JOB "
echo " ====="
# =====
if [ ! $1 ] ; then
    echo " $JOB Computes the Phase Velocity diagram to estimate "
    echo "         the Surface wave dispersion "
    echo "         It uses the suphasevel program "
    echo " "
    echo " Usage: "
    echo " "
    echo " $JOB dt-flnm Mdl00 vn vx "
    echo " "
    echo "         dt-flnm         Data file name             v-1 "
    echo "         Mdl00           Starting Model              v-2 "
    echo "         vn              Minimum S-wave velocity     v-3 "
    echo "         vx              Minimum S-wave velocity     v-4 "
    echo " "
    echo " The output filename is dt-flnm-PDSW.grd "
    echo " note it is a grd file located in $PRJ "
    echo " There is also a dt-flnm-phsV-01.bin in $TMP "
    echo " "
else
    vn=$3
    vx=$4

    hdrvlsu-00.sh $1 | read dt d1 f1 d2 f2 n1 n2 xmx zmx amx amn nyq ofn ofx

    rcphsVX-00.sh $1 300 65 $vn $vx
    PDF-fldrphsV-61.sh $1 $1-00 0 3.9 offset 0 $sofx A4 L O 10 7 75 0.001 "ffid
$1" "Offset (m)" $vn $vx

    cd $TMP

```

```

sk=false

while [ $sk = false ]
do
    pckLine-00.sh $1-phsV-00 $1

    gawk 'END{printf("%i",NR)}' $TMP/phv-$1-02.asc | read nhz
    gawk -v n=$nhz 'BEGIN{printf("%i\n",n)}
                  {printf("%6.3f,%6.2f,%5.2f\n",$1,$2,30.00-NR*(30.00-
4)/(n-1))}' $TMP/phv-$1-02.asc > $TMP/iphv-$1.asc
    cat $GEO_DR/$2.asc $TMP/iphv-$1.asc > $TMP/$1-iswm00.asc
    echo " "
    echo " Inversion Starting ----- "
    echo " "
    sk=true
    swami < $TMP/$1-iswm00.asc > $TMP/$1-oswm00.asc
    echo " "
    echo " Inversion Results ----- "
    echo " "
    cat $TMP/$1-oswm00.asc
    echo " ***** "
    echo " Did SWAMI Converge ???" | tr -d "\012" >/dev/tty
    read response
    case $response in
        y*) sk=true ;;
        n*) sk=false ;;
        *) sk=true ;
    esac
done
if [ $sk = true ] ; then
    swm-00.sh $1
fi
fi

```

5.6 Picking generating ascii files for inversion and plotting

pckLine-00.sh

```

=====
#!/bin/zsh
# =====
# Name of the script
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
echo " ====="
echo " JOB filename -> $JOB "
echo " ====="
# =====
if [ ! $1 ] ; then
    echo " $JOB Script to pick a line from a su formatted file.su "
    echo "      A matrix of numbers "
    echo "      It uses the suximage program "
    echo "      For documentation of how to pick check ximage "
    echo "      module from Seismix Unix "
    echo " "
    echo " Usage: "
    echo " "
    echo " $JOB dt-flnm pck-id "
    echo " "

```

```

echo "          dt-flnm          Data file name          v-1  "
echo "          pck-id          identifier for picked line  v-2  "
echo "                                     "
echo " The output filename is $TMP/pck-v-2                  "
echo " Works in $TMP                                          "
echo "                                                     "
else

ls -l $1.*
pause
ls -l $1.* | read flnm
#ext=`echo "$flnm" | cut -d'.' -f2`
# if [ $ext != "su" ] ; then
#   transformat-00.sh $ext su
#fi
ok=false

while [ $ok = false ]
do
    suximage < $TMP/$1.su mpicks=$TMP/pck-$2-00.asc cmap=hsv6 grid1=solid
grid2=solid gridcolor=black
gawk 'END{printf("%i",NR)}' $TMP/pck-$2-00.asc | read nl
cp -rf $TMP/pck-$2-00.asc $TMP/pck-$2.asc
sugethw < $1.su key=d1 output=geom | gawk 'END{printf("%f\n",2*$1)}' |
read d1
gmt info -C $TMP/pck-$2.asc |
    gawk -v d=$d1 '{printf("%i %f %f %f %f\n", ($2-$1)/d,$1,$2,$3,$4)}'|
read nhz hz0 hz1 phv0 phv1
echo " --- nhz $nhz hz0: $hz0 hz1: $hz1 phv0: $phv0 phv1: $phv1 --- nl:
$nl d1: $d1 ---"
a2b nl=2 outpar=/dev/tty < $TMP/pck-$2.asc > $TMP/pck-$2.bin
unisam nout=$nhz npairs=$nl dxout=$d1 fxout=$hz0 xyfile=$TMP/pck-$2.bin
method=spline > $TMP/phv-$2-01.bin
b2a nl=1 outpar=/dev/tty < $TMP/phv-$2-01.bin |
    gawk -v d=$d1 '{printf("%f %f\n",NR*d,$1)}' |
    gawk -v h=$hz0 '{printf("%f %f\n", $1+h,$2)}' > phv-$2-02.asc
gawk 'END{printf("%i",NR)}' $TMP/phv-$2-02.asc | read nh
suximage < $TMP/$1.su cmap=hsv6 grid1=solid grid2=solid gridcolor=black \
    curve=$TMP/phv-$2-02.asc npair=$nh curvecolor=black
echo " Picks OK? (yes=picks ok, no=repick) " | tr -d "\012" >/dev/tty
read response
case $response in
    y*) ok=true ;;
    n*) ok=false ;;
    *) ok=true ;
esac
done
gawk -v n=$nhz '{printf("%f %f %f\n", $1,$2,30.00-NR*(30.00-4)/(n-1))}'
$TMP/phv-$2-02.asc > phv-$2.asc
gawk -v n=$nhz 'BEGIN{printf("%i\n",n)}
    {printf("%6.3f,%6.2f,%5.2f\n", $1,$2,30.00-NR*(30.00-
4)/(n-1))}' $TMP/phv-$2-02.asc > $TMP/iphv-$2.asc
cat $GEO_DR/Mdl00.asc $TMP/iphv-$2.asc > $TMP/iphv-$2-00.asc
echo "          Picked Dispersion Curve line -> $TMP/phv-$2.asc"
echo "          SWAMI Input file -> $TMP/iphv-$2-00.asc"
fi
=====

```

5.7 Call fldrMASW00.sh for multiple shot gathers

mflldrMASW-60.sh

```

=====
#!/usr/bin/zsh
# X11 Display Shots
# Authors: RC
# NOTE: Comment lines preceeding user input start with  ##
#set -x
# =====
# Name of the scrip
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
echo " ====="
echo " JOB filename -> $JOB "
echo " ====="
# =====
## Set input/output file names and data parameters
if [ ! $1 ] ; then
    echo " $JOB  Generate phase dispersion diagrams/spectra plot the 6mic
"
    echo "          gather and the dispersion analysis diagram          "
    echo "          This scrip needs a rcphsV-???.sh (v-05)                "
    echo "                                                                "
    echo " Usage:                                                                "
    echo "   $JOB   iffid0 iffid1 dffid key pdf-flg                            "
    echo "          iffid0          First-FFID                                v-01    "
    echo "          iffid1          Last-FFID                                v-02    "
    echo "          dffid           Increment in FFID's                        v-03    "
    echo "          Mdl00           Starting Model for inversion              v-04    "
    echo "          SVn             Slow S-wave                               v-05    "
    echo "          SVx             Fast S-wave                               v-06    "
    echo "                                                                "
    echo " The output filename is prfx-pdf-id-pdf.pdf                        "
    echo "                                                                "
else
    iffid=$1  ffidmx=$2  dffid=$3

    export WD=`pwd`
    while (( iffid <= ffidmx )); do
        echo $iffid.su
        if [ -e $iffid.su ]; then
            suop op=avg < $iffid.su |
            suazimuth offset=1 |
            suchw key1=swdep key2=offset a=0 b=1 |
            suchw key1=offset key2=swdep a=0 b=0.1 |
            suop op=norm > $TMP/$iffid.su
            hdrvlsu-00.sh $iffid | read dt d1 f1 d2 f2 ns n2 xmx tmx amx amn nyq
ofn ofx
            echo "Working File -> $iffid max time: $tmx ofx-> $sofx"
            cd $TMP
            fldrMASW00.sh $iffid $4 $5 $6
            pdftk $FIG_DR/$iffid-00.pdf $FIG_DR/$iffid-01.pdf cat output
$FIG_DR/$iffid-MASW.pdf
            okular $FIG_DR/$iffid-MASW.pdf &
            pause
            zap ximage
            zap okular
        fi
        iffid=$((iffid+1))
    done
fi

```

```

        fi
        cd $WD
        pwd
        iffid=$(echo "scale=0;$iffid+$dffid" | bc -l)
    done
fi
=====

```

5.8 2D Vs-profile display

mflldrMASWV-60.sh

```

=====
#!/usr/bin/zsh
# X11 Display Shots
# Authors: RC
# NOTE: Comment lines preceeding user input start with  ##
#set -x
# =====
# Name of the script
full_path=$0
pth=${full_path%/*}
JOB=${full_path##*/}
echo " ====="
echo " JOB filename -> $JOB "
echo " ====="
# =====
## Set input/output file names and data parameters
if [ ! $1 ] ; then
    echo " $JOB  Generate the 2D Swave-Velocity model from the outputs of
"
    echo "          swami it uses the files named: fldr-oswm00.asc.          "
    echo "          check the script SV-MASW2-00.sh, which is applied to      "
    echo "          every file fldr-oswm00.asc                                  "
    echo "          SV-MASW2-00.sh generates a fldr-v.su file (single trace)
"
    echo "          The location of the velocity funcs single trace is stored
"
    echo "          in the headers of the su file.                                "
    echo "          All fldr-v.su files are then integrated into a single      "
    echo "          the filename of this output file is entered by user in      "
    echo "          as variable/parameter v-04. A plot is also generated        "
    echo "
"
    echo " Usage:
"
    echo "   $JOB  iffid0 iffid1 dffif key pdf-flg                                "
    echo "          iffid0          First-FFID                                v-01    "
    echo "          iffid1          Last-FFID                                v-02    "
    echo "          dffid           Increment in FFID's                        v-03    "
    echo "          SV-vel-flnm     filename for velocity model              v-04    "
    echo "
"
    echo " The output filename is prfx-pdf-id-pdf.pdf                          "
    echo "
"
else
    iffid=$1  ffidmx=$2  dffid=$3

    unlink $4.su

    export WD=`pwd`
    while (( iffid <= ffidmx )); do

```

```

        echo $iffid-oswm00.asc
    if [ -e $iffid-oswm00.asc ]; then
        # Creation of the $iffid-v.su file for each $iffid-oswm00.asc
        $EXE/SV-MASW2su-00.sh $iffid-oswm00.asc
        # Integration of all .su files into the Velocity su formatted
velocity model file
        suop op=nop < $iffid-v.su >> $4-00.su
    fi
    cd $WD
    pwd
    iffid=$(echo "scale=0;$iffid+$dffid" | bc -l)
done
    sushw key=d2,f2 a=$dffid,$1 < $4-00.su > $4-v.su
    suximage < $4-v.su legend=1 units="m/s" title="2D S-wave velocity file"
label1="Depth (m)" label2="CDP's"
    transformat-00.sh $4-v su grd
    # Plotting
    PDF-grd-60.sh $4-v VS-$4 A4 L seis 12 -6 "S-wave MASW Velocity Model" CMP
"Depth (m)" 500 "Velocity (m/s)"
fi
=====

```

5.9 Smoothing process

2dVsmooth-00

```

=====
#!/usr/bin/zsh
# Velocity analyses for the cmp gathers
# Authors: Dave Hale, Jack K. Cohen, with modifications by John Stockwell,
Ramon Carbonell
# NOTE: Comment lines preceeding user input start with ##
#set -x
## Set parameters

if [ ! $1 ]; then
    echo " bld2dV-02.sh Fill in a 2D velocity model interpolating and
extrapolating cmps "
    echo " "
    echo " Usage: "
    echo " "
    echo " bld2dV-02.sh flV r1 r2 "
    echo " "
    echo " flV    2D Velocity rms/intt velocity file to interpolate    v1 "
    echo " r1      Smoothing parameter in fast direction                v2 "
    echo " r2      Smoothing parameter in slow direction (Check smooth2)v3 "
    echo " "
    echo " Note:"
else
    flV=$1 r1=$2 r2=$3 nsmooth=$4 it=0

    sugethw < $PRJ/Vel/$flV.su output=geom key=ns,dt | gawk
'END{printf("%i %i %f %i\n",$1,$2,$2/1000000,NR)}' | read ns dt d1 ntr
    echo "ns: $ns dt: $d1 ntr:$ntr"

    sustrip head=$TMP6/$flV-Head.bin < $PRJ/Vel/$flV.su > $PRJ/Vel/$flV-0.bin

    while ((it < nsmooth)); do
        it0=$(echo "scale=0; $it+1" | bc -l)
    done

```



```

        echo "                                G => + Black & - Gray no wiggle trace
        echo "                                "
        echo "                                C => + Red      & - Blue no wiggle trace
        echo "                                "
        echo "    11                                Xsize                                Size of plot in X axis
        echo "                                "
        echo "                                if negative plots the action flipped right-to-left if = 0 fill
al surface of paper "
        echo "    12                                Zsize                                Size of plot in Y axis                                if = 0 fill
al surface of paper "
        echo "    13                                Amgain                                Amplitude Gain (Increases the Blackness of the plot 0, w modes)
        echo "                                "
        echo "    14                                Amp-bias                                Controles the constrast
        echo "                                "
        echo "    15                                Title                                Title of the plot
        echo "    16                                Tlabel                                Lable for the Time axis (Lable for X axis is dependent on v
5)
        echo "    17                                SVMn                                Minimum Shear-Wave velocity (m/s)
"
        echo "    18                                SVMx                                Maximum Shear-Wave velocity (m/s)
"
        echo "                                "
        echo "                                "                                Example
        echo "                                "
        echo "                                "
        echo "    $JOB prfx-fl prfx-pdf 0 14 cdp 100 2000 A4 L O 20 12 10 0.001 Title_File_name_Stak
xlab tlab Svn Svx "
        echo "                                "
        echo "                                "                                IMPORTANT
        echo "                                "
        echo "                                "
        echo "    psseg is called more than onece when plotting a file with more than 10000 traces
        echo "                                "
        echo "    PaperSize (in cm) Short Axis, long Axis (This is usefull to stablsh Xsize and
Zsize)
        echo "                                "
        echo "                                letter                                21.6                                27.9                                8.5 x 11.0 in
"
        echo "                                A4                                21.0                                29.7                                8.3 x 11.7 in
"
        echo "                                A3                                29.7                                42.0                                13.0 x 19.0 in
"
        echo "                                A2                                42.0                                59.4                                16.5 x 23.4 in
"
        echo "                                A1                                59.4                                84.1                                23.4 x 33.1 in
"
        echo "                                A0                                84.1                                118.9                                31.1 x 46.8 in
"
        echo "                                "
else
#-----
#    Generate a Hardcopy
#-----

# Plotting Paramters -----

psfl=$1.00
gmt begin $psfl pdf
gmt6stRC.sh paper $8 $9 $11 $12
source $TMP6/gmtvar.conf

tmn=$3 tmx=$4 x6mn=$6 x6mx=$7 ifv=1

Ampgain=$(echo "scale=2; $13*10" | bc -l)
ampbias=$14
COMM="$15 - Shear-Wave Vel (red slopes): $17 $18 (m/s)"
ttitle=$16
if [ ! $16 ] ; then
    ttitle="Time (s)"

```

```

fi

#cp $1.su $TMP/.
cd $TMP

sugethw < $1.su output=geom key=trid | gawk ' END{printf("%i \n",$1)}' | read itid
if (( $itid == 123 )) ; then ifv=-1 fi

pnlfrm.ssh abs $ifv $1 ps.$1.00

case "$5" in
  nstrec){
    if xtitle="Station Rec #"
    hp=b
    suchw key1=tracr key2=$5 < $TMP6/ps.$1.00.su > $TMP6/ps.$1.01.su
    suop op=nop < $TMP6/ps.$1.01.su > $TMP6/ps.$1.00.su
    } ;;
  tracf) {
    xtitle="Trace #"
    hp=b
    suchw key1=tracr key2=$5 < $TMP6/ps.$1.00.su > $TMP6/ps.$1.01.su
    suop op=nop < $TMP6/ps.$1.01.su > $TMP6/ps.$1.00.su
    } ;;
  tracl) {
    xtitle="Trace #"
    hp=b
    suchw key1=tracr key2=$5 < $TMP6/ps.$1.00.su > $TMP6/ps.$1.01.su
    suop op=nop < $TMP6/ps.$1.01.su > $TMP6/ps.$1.00.su
    } ;;
  tracr) {
    xtitle="Trace #"
    hp=b
    } ;;
  cdp) {
    xtitle="CDP's #"
    hp=c
    } ;;
  offset) {
    xtitle="Offset (m)"
    hp=o
    } ;;
esac

echo "
echo "   Input Parameters:
echo "
echo "   Data file to process      -> $1.su
echo "   PDF file                  -> $2.pdf
echo "
echo "   tmn      -> $3           first time of plot
echo "   tmx      -> $4           last time to plot
echo "   offset/cdp/tracr -> $5   offset => Offset cdp => CDP and tracr=> trace num (tracr)
echo "   min      -> $6           first trace/cdp/offset
echo "   max      -> $7           last trace/cdp/offset
echo "   A0/A3/A4 -> $8           Paper Size A0/A3/A4
echo "   P/L      -> $9           Portrait/Landscape
echo "   W/O/G/C  -> $10          W => Wiggle Trace O => Black No Wiggle Trace
echo "                               U => Wiggle Trace only
echo "                               G => + Black & - Gray no wiggle trace
echo "                               C => + Red   & - Blue no wiggle trace
echo "   Xsz      -> $11          Size of the X and/or horizontal axis
echo "                               if negative plots the section flipped right-to-left
echo "   Zsz      -> $12          Size of the Z and/or vertical axis
echo "   Amgain   -> $13          Amplitude Gain, Increases the blackness of the plot
echo "   ampbias  -> $14          Amplitude bias
echo "   Title    -> $15          Title of the plot
echo "   Xlbl     -> $16          Xlabel (lble for the Xaxis)
echo "   SVmn     -> $17          Minimum Shear-Wave velocity (m/s)
echo "   SVMx     -> $18          Maximum Shear-Wave velocity (m/s)
echo "
echo "   Figure size      -> $Xsz $Ysz
echo "   Paper Size      -> $XPaper $YPaper

suop op=nop < $TMP6/ps.$1.00.su |
suwind key=$5 min=$x6mn max=$x6mx |
sushw      key=tracl,trid,d1,d2,f1,f2,mark,ungpow,unscale,ntr      a=1,1,0,0,0,0,0,0,0,0
b=1,0,0,0,0,0,0,0,0,0 |

```

```

suop op=nop > $TMP6/ps.$1.01.su

sugethw < $TMP6/ps.$1.01.su output=geom key=ns,dt,trid |
    gawk ' END{printf("%i %i %f %f %i %i\n",$1, $2, $2/1000000, ($1-1)*($2/1000000), NR,$3)}'
| read ns dt dl txx ntr itid
if (( $itid == 123 )) ; then ifv=-1 fi

echo "      Number of traces -> $ntr"

AnotTicks xmn=$x6mn xmx=$x6mx ymn=$tmn ymx=$tmx nx=7 ny=10 | read xtick xanot ttick tanot

gmt basemap -JX$Xsz/-Y$ysz -R$x6mn/$x6mx/$tmn/$tmx -X4.0 -Y4.0 \
    -Bxa"$xanot"+l$xtitle -Bya"$tanot"f"$ttick"+l$tttitle -BWEsN

dmx=$(echo "scale=8; ($Ampgain*$Xsz)/($x6mx-($x6mn))" | bc -l)
cmx=$(echo "scale=8; $dmx*100000000" | bc -l)
echo "
echo "*** $JOB **      dmx-> $dmx      cmx-> $cmx      x6mx-> $x6mx ***"
echo "*** $JOB ** xt看-> $xtick xanot-> $xanot ttick-> $ttick x6mn-> $tanot ***"
itrc=0
while ((itrc <= ntr )); do
    itrcw=$(echo "$itrc+$nwtrc" | bc -l)
    echo "*** $JOB ** Num Traces-> $itrc $itrcw $nwtrc $ntr"
    echo "
    suwind key=trac1 min=$itrc max=$itrcw < $TMP6/ps.$1.01.su > $TMP6/ps.$1.02.su
    segyhdrs < $TMP6/ps.$1.02.su bfile=$TMP6/ps0.PSb.$1.bin hfile=$TMP6/ps0.PShd.$1.asc
    segywrite tape=$TMP6/ps.$1.00.sgy conv=0 format=5 endian=0 hfile=$TMP6/ps0.PShd.$1.asc
    bfile=$TMP6/ps0.PSb.$1.bin < $TMP6/ps.$1.02.su

    case "$10" in
        O) {
            echo " Black and White no wiggle -> $hp"
            gmt segy $TMP6/ps.$1.00.sgy -F"$fgrnd" -D$dmx -C$cmx -Z -Qb$ampbias -S$hp -I
            } ;;
        G) {
            echo " Black and Gray no wiggle -> $hp"
            gmt segy $TMP6/ps.$1.00.sgy -F"$gry3" -D$dmx -C$cmx -Z -Qb-$ampbias -S$hp
            gmt segy $TMP6/ps.$1.00.sgy -F"$fgrnd" -D$dmx -C$cmx -Z -Qb$ampbias -S$hp -I
            } ;;
        C) {
            echo " Blue and Red no wiggle -> $hp"
            gmt segy $TMP6/ps.$1.00.sgy -F"$red0" -D$dmx -C$cmx -Z -Qb-$ampbias -S$hp
            gmt segy $TMP6/ps.$1.00.sgy -F"$blue0" -D$dmx -C$cmx -Z -Qb$ampbias -S$hp -I
            } ;;
        W) {
            echo "Wiggle trace Black and White -> $hp"
            gmt segy $TMP6/ps.$1.00.sgy -F"$fgrnd" -W -D$dmx -C$cmx -Z -Qb$ampbias -S$hp
            } ;;
        U) {
            echo "Wiggle trace -> $hp"
            gmt segy $TMP6/ps.$1.00.sgy -W -D$dmx -C$cmx -Z -Qb$ampbias -S$hp
            } ;;
    esac
    itrc=$(echo "$itrc+$nwtrc" | bc -l)
done

#-----
txn=$(echo "scale=3;$x6mx/$18" | bc -l)
txx=$(echo "scale=3;$x6mx/$17" | bc -l)
echo "0.0 0.0 \n $x6mx $txn \n $x6mx $txx \n 0.0 0.0" > $TMP/$1-vnx.asc
gawk '{printf("%f %f \n",$1,$2)}' $TMP/$1-vnx.asc | gmt plot -X0.0 -Y0.0 -Wthick,red -V
#-----
if [ ! -f $1-phsV-00.grd ] ; then
    transformat-00.sh $1-phsV-00 su grd
fi
#-----

gmt grdinfo -C $TMP/$1-phsV-00.grd | read tmp xmn xmx ymn ymx zmn zmx dx dy ny nx
gmt grd2cpt $TMP/$1-phsV-00.grd -Cseis -V -Z -A+70 -Ic

echo " $JOB # xmn-> $xmn xmx-> $xmx dx-> $dx nx-> $nx "
echo " $JOB # ymn-> $ymn ymx-> $ymx dz-> $dy nz-> $ny "
echo " $JOB # vmn-> $zmn vmx-> $zmx "

AnotTicks xmn=$xmn xmx=$xmx ymn=$ymn ymx=$ymx nx=6 ny=6 | read xt看 xanot ztick zanot
gmt basemap -JX$Xsz/-Y$ysz -R$xmn/$xmx/$ymn/$ymx -X$Xrc0 -Y0.0 \
    -Bxa"$xanot"+l"Phase Velocity (m/s)" -Bya"$zanot"f"$ztick"+l"Frequency (hz)" -BWEsN

```

```

gmt grdimage $TMP/$1-phsV-00.grd -V -C
gmt psscale -DJMR+v -C -B0.1+1"Amplitude"
#-----

gmt text -JX15/4 -R0/15/0/4 -V -N -X-$Xrc0 -Y-1.75 -F+f+j+a <<- END
0.3 0.80 10p,Helvetica-Bold LB 0 $COMM
0.3 0.45 8p,Helvetica-Oblique, LB 0 $PRJ
0.3 0.10 8p,Helvetica-Oblique,blue LB 0 Files-> Data: $1.su $1-phsV-00 PDF Image: $2.psdf
END

gmt end

if [ $FIG_DR ] ; then
mv $psfl.pdf $FIG_DR/$2.pdf
okular $FIG_DR/$2.pdf &
echo " View PDF Image file-> okular $FIG_DR/$2.pdf "
else
mv $psfl.pdf $TMP/$2.pdf
okular $TMP/$2.pdf &
echo " View PDF Image file-> okular $TMP/$2.pdf "
fi

fi

=====

```

APPENDIX 6. SUPPLEMENTARY FIGURES OF THE RESULTS AND MODEL INTERPRETATIONS

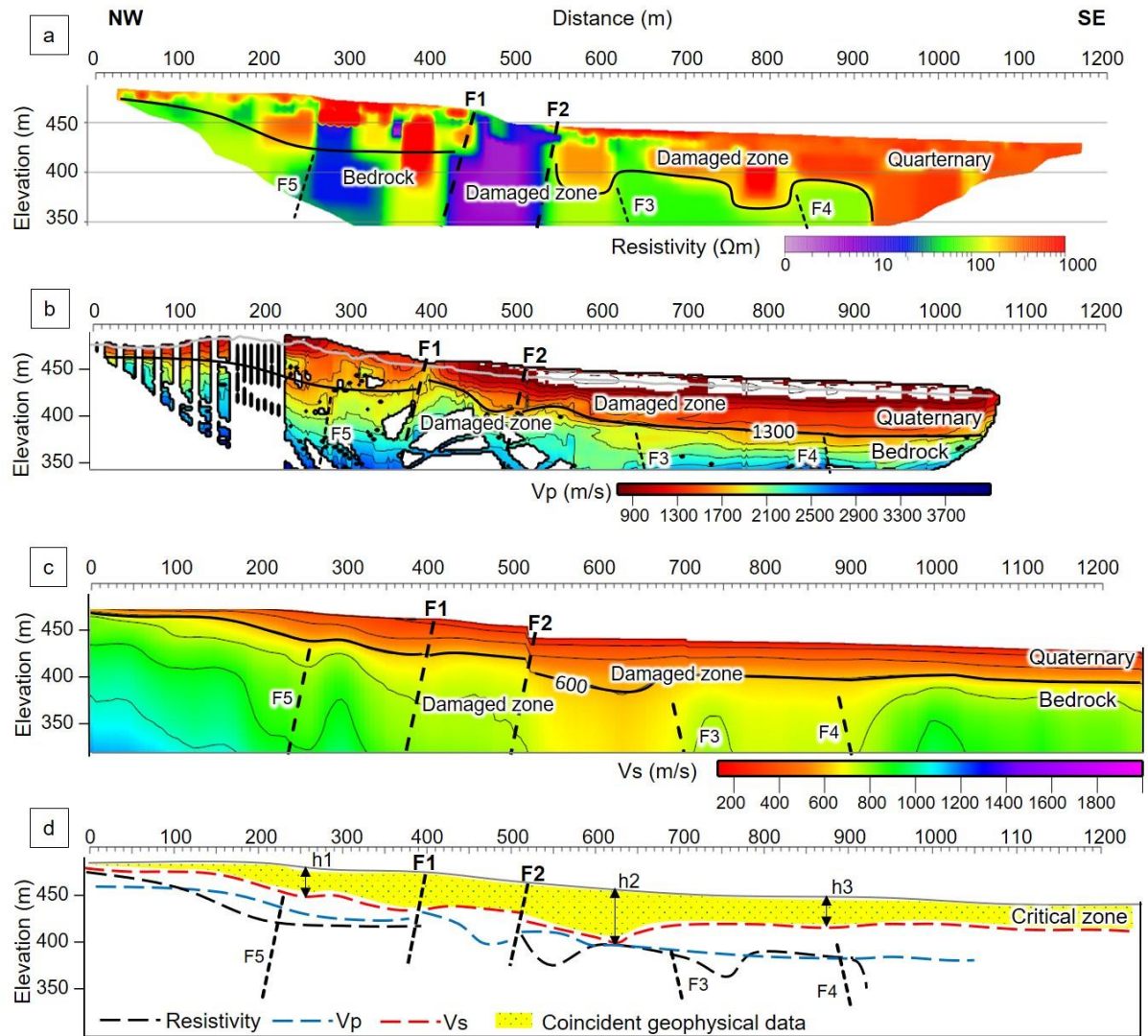


Figure A. The image fault- and damaged- interpretations of La Torrecilla profile: a) The resistivity model; b) The P-wave velocity model; c) The S-wave velocity model; and d) The integration of geophysical interpretation of the base of CZ.

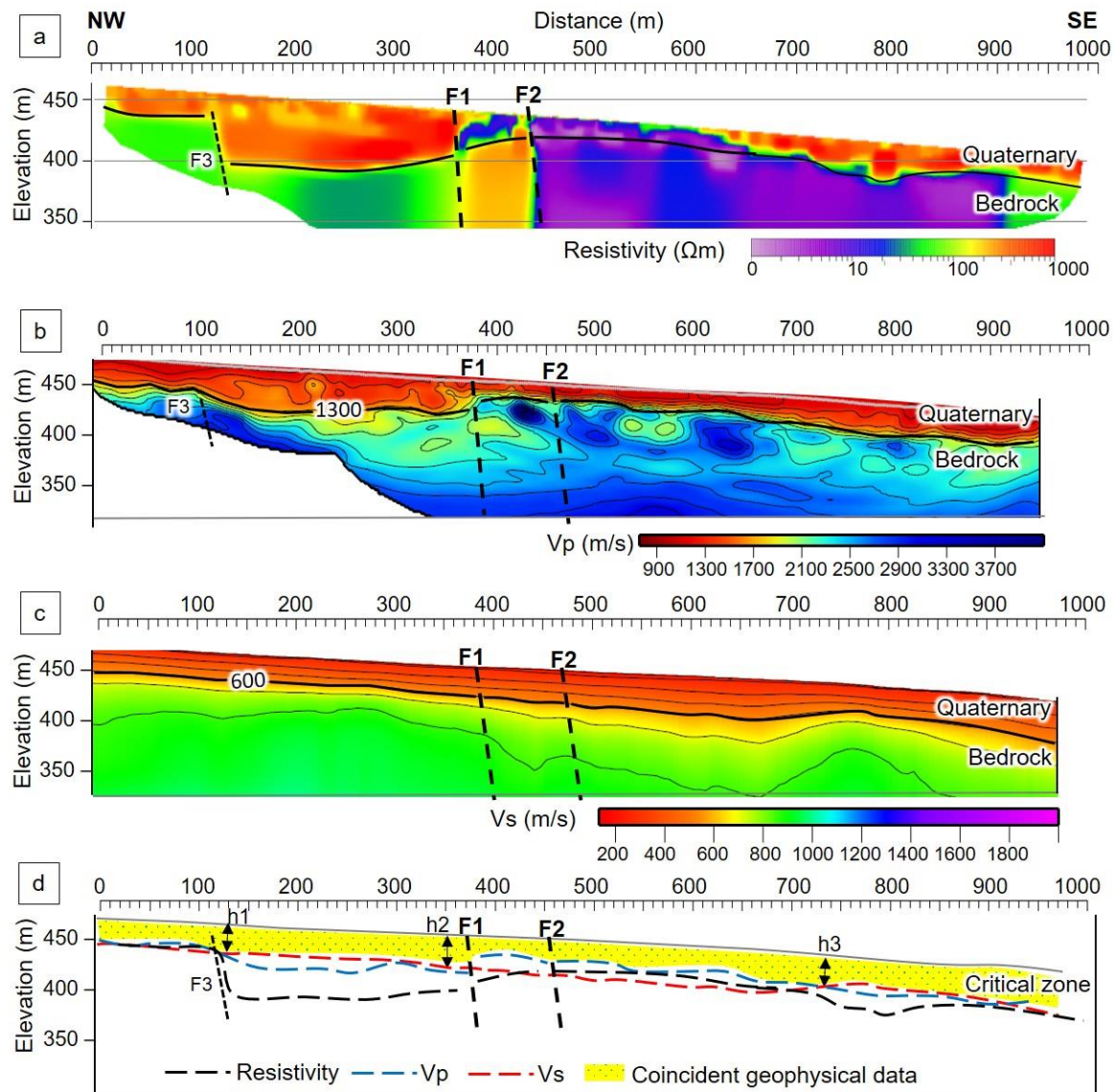


Figure B. The image fault- and damaged- interpretations of La Salud North profile: a) The resistivity model; b) The P-wave velocity model; c) The S-wave velocity model; and d) The integration of geophysical interpretation of the base of CZ.

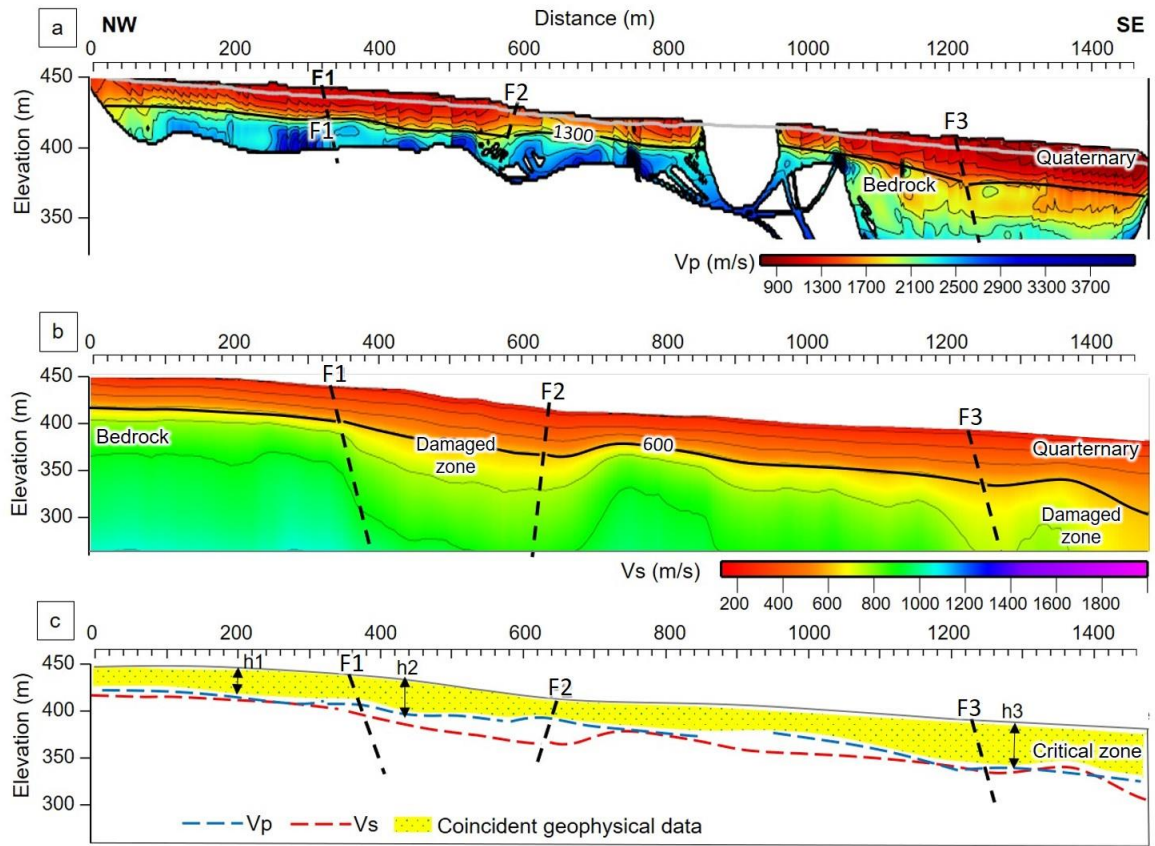


Figure C. The image fault- and damaged- interpretations of La Salud South profile: a) The P-wave velocity model; b) The S-wave velocity model; and c) The integration of geophysical interpretation of the base of CZ.

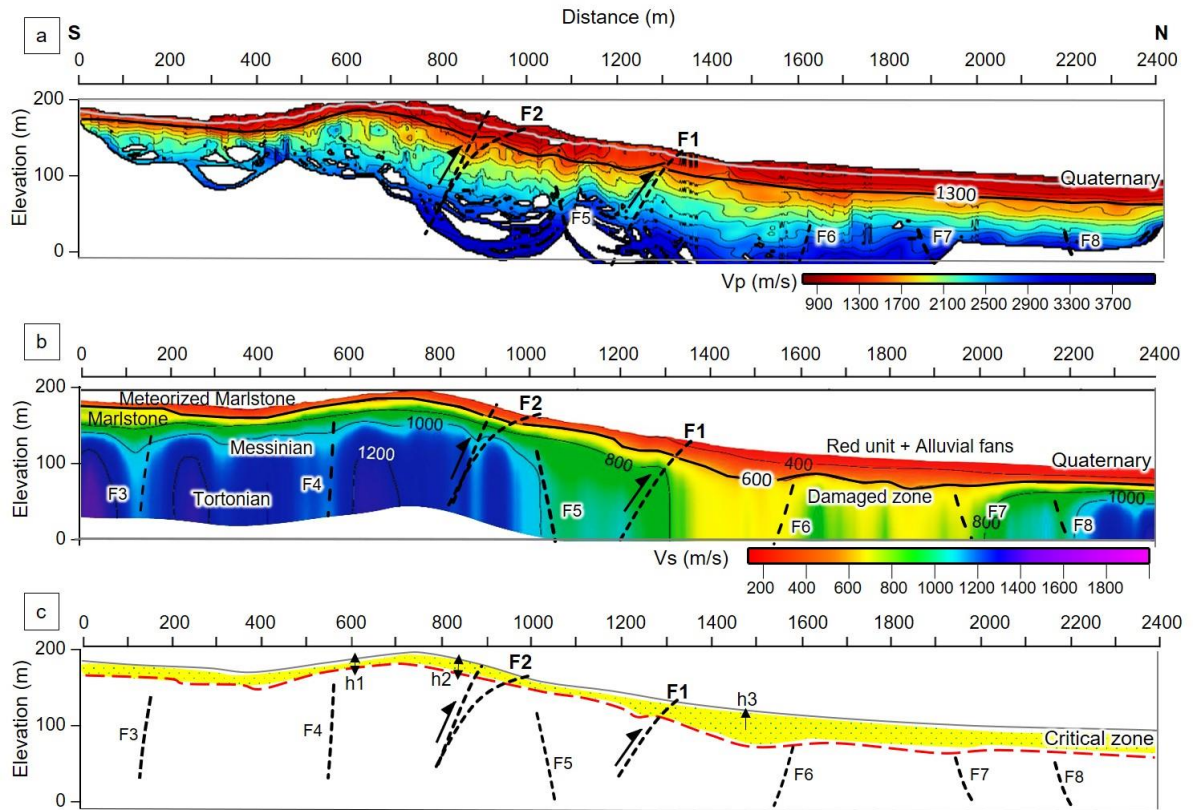


Figure D. The image fault- and damaged- interpretations of Carrascoy profile: a) The P-wave velocity model; b) The S-wave velocity model; and c) The integration of geophysical interpretation of the base of CZ.