Advances in Seismic Diffractions Imaging: Preliminary Results of a Systematic Literature Review

Guilherme Zakarewicz[1], Susanne Maciel[2], Luciano Cunha[1], [1]Universidade de Brasília (UnB), [2]Faculdade UnB Planaltina (FUP)

This paper was prepared for presentation during the 18th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 October 2023.

Abstract

Seismic diffractions are often treated as noise during conventional processing workflows, but they hold valuable information about small-scale subsurface structures. By separating and imaging the diffracted wavefield, higher resolution images can be achieved. This study presents a systematic literature review (SLR) on seismic diffractions imaging, aiming to provide a comprehensive overview of the current state-of-the-art and identify new research directions. Through structured and quantitative analysis of primary studies, we integrated and synthesized multiple papers, offering valuable insights into the publication trends, influential publications, prominent research directions, geographic distribution, and main applications. Co-citation and bibliographic coupling networks provided insights into the thematic and methodological connections among publications, showing influential works and cohesive research clusters. Furthermore, we noticed that emerging research focuses on coal mining and ground-penetrating radar (GPR) data applications.

Introduction

Seismic diffractions are the result of the interaction of the seismic waves with small-scale obstacles as faults, fractures, pinch-outs, and karsts. They carry significant information about these subsurface features, offering valuable insights into their characteristics (Bansal & Imhof, 2005). An intriguing aspect of diffraction wavefield is its theoretical potential for achieving "superresolution," surpassing the traditional Rayleigh limit of half the seismic wavelength (Tschannen et al., 2020). A significant challenge in obtaining high-resolution images lies in the fact that the diffracted component of the wavefield is often considered as noise in traditional preprocessing workflows. Diffracted signals have much weaker amplitudes, typically two or three orders of magnitude lower than the traditional reflections (Klem-Musatov, 1994). Traditional processing kernels are biased against diffractions to enhance the reflected wavefield. Consequently, a substantial portion of the wavefield remains underutilized in subsurface imaging, leading to the loss of valuable information. Unlike reflections, which arise from smooth interfaces, diffractions stem from small-scale structures and do not conform to the general conditions of the ray theory outlined by Červeny (2001). As a result, it becomes possible to obtain subsurface images that predominantly consist of diffractions, offering higher resolution (Lin et al., 2020). Additionally, the extracted diffractions can be utilized for velocity analysis purposes (Fomel et al., 2007; Reshef & Landa, 2009; Delf et al., 2022).

Currently, various methods have been developed for the separation and imaging of seismic diffractions: the plane-wave destruction (PWD) (Fomel et al., 2007), anti-stationary phase filter (Moser & Howard, 2008), focus-mute-defocus (Khaidukov et al., 2004), multifocusing (Berkovitch et al., 2009), separations in the dip-angle migration domain (Klokov & Fomel, 2012), and machine learning (ML)-based approaches (De Figueiredo et al., 2013; Maciel & Biloti, 2020). There are currently a few options for reproducible codes specifically designed for diffractions imaging. One example is the set of functions for performing (PWD) available in the Madagascar software (Fomel et al., 2013). Another available software is DiffraPy, which implements the anti-stationary phase filter approach, available at github.com/GuilhermeZakarewicz/DiffraPy.

The systematic literature review (SLR) is a rigorous and transparent process used to minimize bias in qualitative analysis (Tranfield et al., 2003). Its purpose is to identify gaps in a specific theme or field of study, provide a comprehensive summary of relevant studies on a particular topic, and perform a qualitative analysis of the extracted data (Castro & Cunha, 2021). The meta-analysis is a subset of the SLR that focuses on quantitative analyzis. It involves assessing the results of primary studies to draw more robust conclusions (Haidich, 2010). Therefore, the objective of this work is to conduct a systematic review focused on seismic diffractions imaging. Through this review, we will perform a comprehensive and structured analysis of primary studies, providing an overview of the current state-of-the-art. Our aim is to advance knowledge in seismic diffractions imaging and provide insights on future trends and possible gaps on this field of knowledge.

Materials and Methods

Using the Web of Science (WOS) and Scopus databases, we conducted a keyword search for "seismic diffraction" and "imaging" within the time frame from January 1st, 1990, to August 5th, 2022. Both databases returned a total of 1536 publications during this period. We followed the PRISMA statement guidelines (Moher et al., 2009) for the manual selection of articles for quantitative synthesis.

After removing duplicates, assessing full-text articles, and applying predefined criteria, we included a total of 150 articles for our analysis. The exclusion criteria during the screening phase encompassed non-article works (e.g., books, book chapters, conference abstracts, theses), articles unrelated to seismic diffraction separation, papers not written in English, and non-peer-reviewed works.

For analyzing the selected papers and constructing bibliometric networks, we used the VOSViewer software, version 1.6.18 (Van Eck & Waltman, 2010). The software enables the generation of networks using various criteria such as co-citation (measuring the relatedness of items based on their shared citations), co-authorship (based on the number of co-authored documents), and bibliographic coupling (assessing the similarity of papers based on shared references).

Results and Discussion

The number of articles published over the years and their direct citation are shown in Figure 1. There has been a notable increase in the number of published articles, particularly since the 2010s, with a total of 137 papers published since this period. While seismic diffractions applications have been explored since the 1950s (Krey, 1952; Kunz, 1960; Trorey, 1970), it was not until after 1990 that robust and reliable workflows specifically dedicated to diffractions processing emerged, e.g., Landa & Keydar (1998); Fomel (2002); Khaidukov et al. (2004). The observed increase in the number of published articles and the subsequent rise in citation counts highlight the growing significance of seismic diffractions as a research topic. This expansion reflects the continuous efforts made by researchers to enhance the understanding of diffraction phenomena and their applications in various fields, including exploration geophysics, subsurface imaging, and reservoir characterization.

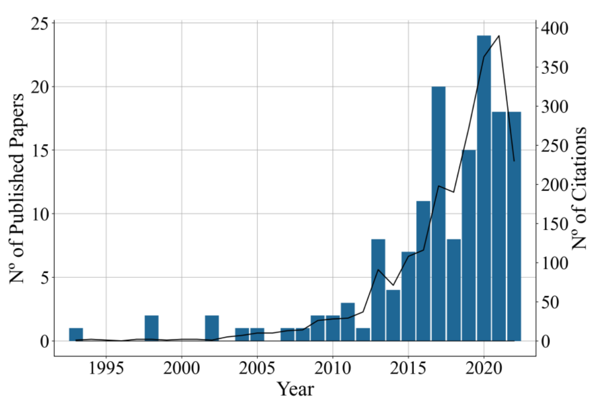

Figure 1 – Evolution of the number of publications regarding "seismic diffractions imaging" (blue) and number of citations (black) since 1990.

We utilized the Python library wordcloud (Oesper et al., 2011) to generate visual representations of the words that appeared most frequently in the titles, abstracts, and keywords of the publications (Figure 2). This approach allowed us to visually present the prominent terms and concepts that are prevalent in the analyzed dataset and highlight the key themes and topics that are frequently discussed in the literature. Among the most frequent words observed in the analyzed publications, several terms stand out as key indicators of the main research topic. These include "diffraction" (440), "diffractions" (259), "seismic" (388), "imaging" (233), and "method" (204), which underscore the central focus of the research theme. Specific words such as "migration" (118) were prominently featured, indicating the significance of studies where the migration kernel plays a fundamental role (Moser & Howard, 2008; Khaidukov et al., 2004; Berkovitch et al., 2009). The term "synthetic" (82) suggests the utilization of synthetic applications as a means to test and validate various methods within the field (Ford et al., 2021; Maciel & Biloti, 2020; Dell & Gajewski, 2011; Tschannen et al., 2020). The term "dip-angle" (52) indicates the relevance of works that leverage the geometric differences between diffractions and reflections in the dip-angle migrated domain to separate them (Klokov & Fomel, 2012; Dafni & Symes, 2017), and "plane-wave" (44) indicates the application of the plane-wave destruction method (Fomel et al., 2007) in relevant research papers (Decker et al., 2017; Li et al., 2022).

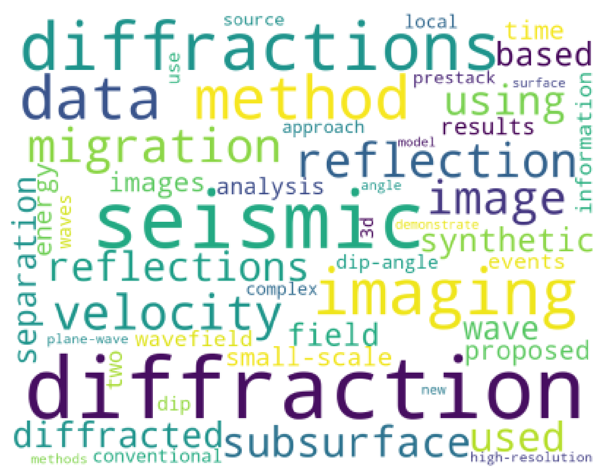

Figure 2 – Word cloud with the 50 most frequent words in the titles, abstracts and keywords from the 150 articles of both databases (WOS and Scopus). The typographic dimensions are related to the number of occurrences.

Figure 3 illustrates the co-citation network.In this analysis, the proximity of two documents on the map indicates the frequency with which they are cited together in other works. Hence, publications that are cited together more frequently tend to be closer to each other on the map, suggesting a degree of thematic or methodological similarity. The circles' size are determined by the number of times the publications are cited. The network does not consider the initial year of the query, which means it includes works that may be references on the topic rather than focusing solely on the selected time span. The co-citation network reveals a distinct cluster (highlighted in red) consisting of the ten most cited works: Khaidukov et al. (2004); Kanasewich & Phadke (1988); Landa & Keydar (1998); Fomel (2002); Fomel et al. (2007); Moser & Howard (2008); Berkovitch et al. (2009); Klokov & Fomel (2012); Landa et al. (1987); Dell & Gajewski (2011). This clustering suggests a close proximity among these publications in terms of their applied methods and approaches, and their influential role within the research community.

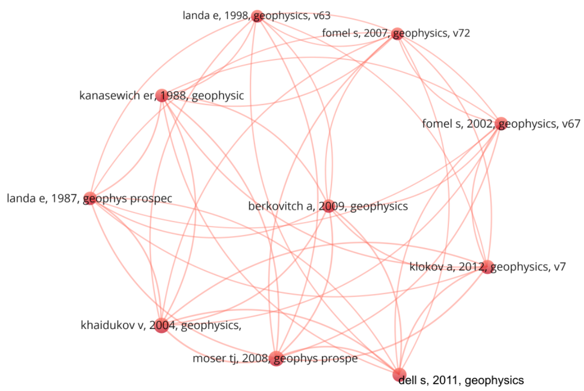

Figure 3 – Co-citation map for the WOS database using documents as unit of analysis and citations as weight.

The analysis of bibliographic coupling networks, as shown in Figure 4, provides insights into the interconnections among papers based on shared references. The distance between two circles and the thickness of the lines are determined by the number of cited references two publications have in common. In this study, we focused on papers published within the last 5 years to capture the most recent developments in the field. Examining the WoS map (Figure 4a), we observed a single cluster comprised of Zhao et al. (2020); Merzlikin et al. (2019); Zhang et al. (2019); Tschannen et al. (2020); Bauer et al. (2019), with the work of Lin et al. (2020) as the nucleus. On the other hand, the Scopus map (Figure 4b) revealed two distinct clusters. The first cluster, marked by red, includes papers such as Khoshnavaz et al. (2018); Li et al. (2021); Zhao et al. (2019a), indicating a separate research focus within the broader field. The second cluster, marked by green, is represented solely by Wang et al. (2020), suggesting a different line of inquiry.

Figure 5 provides an overview of the number of publications per country based on the first author's affiliation. The data reveals that a significant proportion of the papers are authored by researchers affiliated with institutions in China (46) and the United States (33). Among the works present in the database, a total of six publications were authored by researchers affiliated with Brazilian institutions. These institutions include Universidade de Brasília (UnB), Universidade de Campinas (Unicamp), Universidade Federal Fluminense (UFF), and Universidade Federal do Pará (UFPA). We highlight the works of De Figueiredo et al. (2013) and Maciel & Biloti (2020),

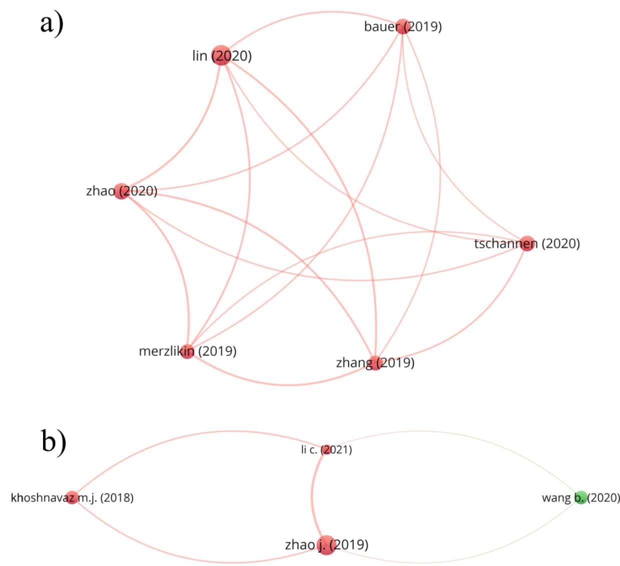

Figure 4 – Bibliographic coupling map for the (a) WoS and (b) Scopus databases for the last 5 years using documents as unit of analysis and normalized citations as weight.

which present machine learning (ML) techniques for diffractions separation and imaging; Santos et al. (2020), who performed the diffraction velocity analysis after the PWD filtering on a single-channel seismic survey; and Coimbra et al. (2018), which derived a finite-offset double-square-root (FO-DSR) diffraction time equation for constructing D-volumes, i.e., datasets solely composed of diffractions.

The work by De Figueiredo et al. (2013) is considered a pioneering study in the application of machine learning (ML) techniques for the separation and imaging of seismic diffractions. In their research, the authors employed the k-nearest neighbors technique (kNN) to distinguish diffractions from noise and reflections. This approach represented an initial step in utilizing ML algorithms for the automated identification and characterization of diffractions in seismic data. Maciel & Biloti (2020) presented a new way to describe seismic events based on statistical parameters, which enabled the use of support vector machines (SVMs) to separate diffraction events from reflections. The Center for Petroleum Studies (CEPETRO) and the Department of Applied Mathematics at Unicamp have made significant contributions to the field of diffraction imaging. Their research includes works by Gelius et al. (2013); Coimbra et al. (2018); Asgedom et al. (2013), which applied diffractions imaging techniques to analyze a marine dataset from the Jequitinhonha Basin (offshore Brazil).

After conducting a thorough review of the 150 selected papers, we categorized them based on their primary applications, as shown in Figure 6. Among the various applications, the most prevalent one is the characterization and delineation of faults, fractures, and other small-scale discontinuities to enhance the resolution of subsurface

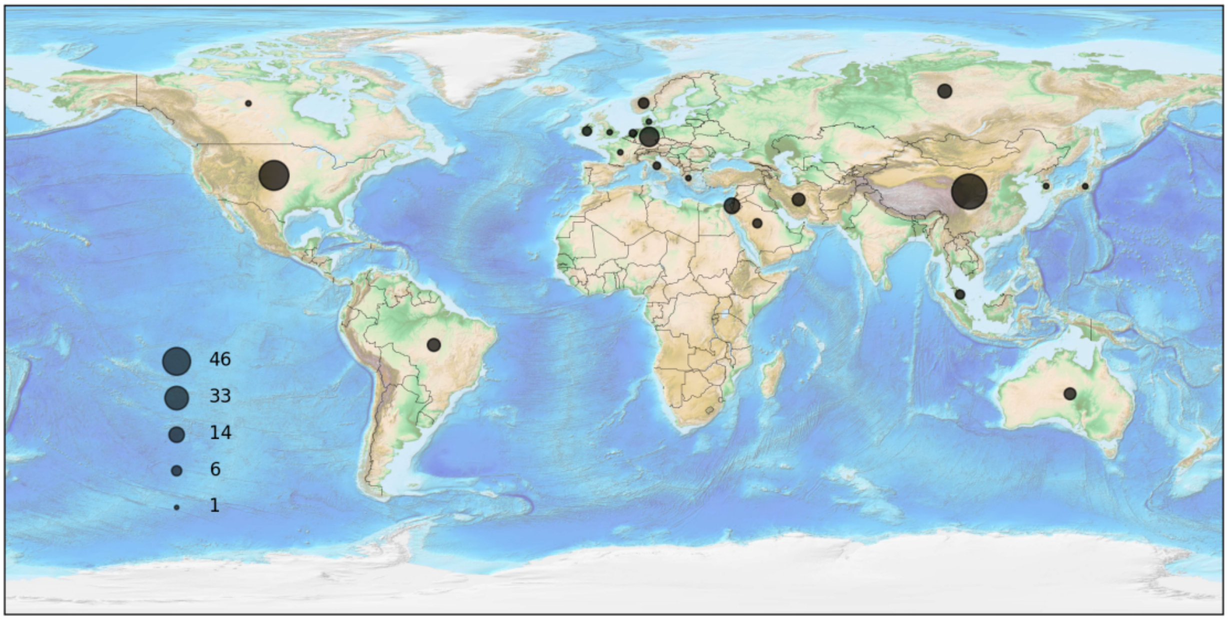

Figure 5 – Number of published articles per country.

imaging (Tschannen et al., 2020; Moser & Howard, 2008; Khaidukov et al., 2004; Grasmueck et al., 2013). This category accounts for a total of 75 papers, indicating the significance of utilizing seismic diffraction analysis in improving subsurface imaging quality. Another prominent application, observed in 42 papers, is the use of seismic diffractions processing in the oil and gas industry (Decker et al., 2014; Tyiasning et al., 2016; Bashir et al., 2018). These studies primarily focus on identifying structures and features associated with the presence of hydrocarbons. 14 papers delve into the application of seismic diffractions in near-surface investigations. These studies focus on the identification of pipes, archaeological investigations, and other utility-related purposes, highlighting the versatility of diffraction analysis in various practical scenarios (Maciel & Biloti, 2020; Landa & Keydar, 1998; De Figueiredo et al., 2013). 6 papers concentrate on velocity analysis techniques necessary for migration processes involving seismic diffractions separation (Fomel et al., 2007; Dell & Gajewski, 2011; Santos et al., 2020). 6 papers specifically examine the implications of seismic diffractions in the coal mining industry, highlighting the significance of diffraction analysis in delineating coal seams and preventing water inrush and coal outbursts (Li et al., 2020; Zhou et al., 2017; Wang et al., 2020). This emerging application is gaining recognition within the scientific community, with recent publications of notable significance. 7 works focus on other applications, such as the characterization of mass-transport complexes (Ford et al., 2021).

We identified seven recent studies that focused on the separation of diffractions in radargrams obtained through the ground-penetrating radar (GPR) method, e.g., Maciel & Biloti (2020); Zhao et al. (2019b); Yuan et al. (2019). GPR is a non-destructive geophysical imaging technique widely utilized in numerous applications, such as geotechnical engineering, archaeology, forensics investigations (Castro & Cunha, 2021), and imaging of tree roots (de Aguiar et al., 2021). Despite being based on the emission of electromagnetic waves, GPR exhibits kinematic behavior similar to seismic reflection acquired with common offset methods. By studying diffractions in GPR radargrams, researchers can further enhance their understanding of subsurface features and improve the resolution of GPR imaging in various practical contexts. Out of the total analyzed papers, the seven articles that incorporate GPR data comprise only 6% of the dataset. Despite their relatively small proportion, these papers are noteworthy as they indicate a new and emerging trend in the application of seismic diffractions imaging. While the inclusion of GPR data in seismic diffractions imaging is an emerging trend, further research is necessary to fully assess its potential

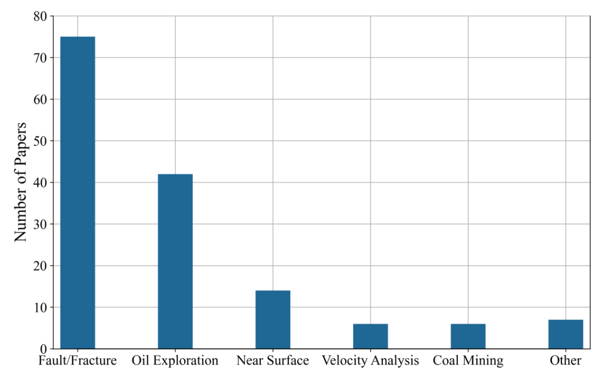

Figure 6 – Main applications of the 150 analyzed papers.

and gain a comprehensive understanding of its limitations.

Conclusion

After analyzing the 150 selected papers, we identified the most influential publications in the topic. The co-citation network highlights their significant contributions, as their methods are widely explored. Furthermore, analyzing specific terms from the word cloud revealed important research directions and techniques. The geographic distribution of publications revealed a significant contribution from researchers affiliated with institutions in China and the United States. However, there are notable works from Brazilian institutions which showcased the application of ML techniques and velocity analysis. Despite Brazil's substantial mineral and petroleum potential, the utilization of diffraction imaging as a technique remains relatively underexplored within the country. The main applications of seismic diffractions imaging include small faults and fracture characterization, oil and gas exploration, and near-surface investigations. Our observation is that emerging researches focus on coal mining and the application of GPR data, suggesting that diffraction imaging techniques hold promise for enhancing near-surface studies. We are currently working on a more complete review of the theme to delve deeper into the growth, significance, and diverse applications of seismic diffractions imaging.

References

Asgedom, E. G., Gelius, L. J. & Tygel, M., 2013. 2D common-offset traveltime based diffraction enhancement and imaging, Geophysical Prospecting, vol. 61(6): 1178–1193.

Bansal, R. & Imhof, M. G., 2005. Diffraction enhancement in prestack seismic data, Geophysics, vol. 70(3): V73–V79.

Bashir, Y., Ghosh, D. P. & Sum, C. W., 2018. Influence of seismic diffraction for high-resolution imaging: Applications in offshore Malaysia, Acta Geophysica, vol. 66(3): 305–316.

Bauer, A., Schwarz, B., Werner, T. & Gajewski, D., 2019. Unsupervised event identification and tagging for diffraction focusing, Geophysical Journal International, vol. 217: 2165–2176.

Berkovitch, A., Belfer, I., Hassin, Y. & Landa, E., 2009. Diffraction imaging by multifocusing, Geophysics, vol. 74: WCA75–WCA81.

Castro, K. C. P. L. & Cunha, L. S., 2021. Forensic investigations with the identification of human remains with ground penetrating radar (GPR): A review, Estudos Geológicos (UFPE), vol. 31(2): 64–86.

Coimbra, T. A., Faccipieri, J. H., Speglich, J. H., Gelius, L.-J. & Tygel, M., 2018. Enhancement of diffractions in prestack domain by means of a finite-offset double-square-root traveltime, Geophysics, vol. 84(1): V81–V96.

Dafni, R. & Symes, W. W., 2017. Diffraction imaging by prestack reverse-time migration in the dip-angle domain, Geophysical Prospecting, vol. 65(S1): 295–316.

de Aguiar, G. Z., Lins, L., de Paulo, M. F., Maciel, S. T. R. & Rocha, A. A., 2021. Dielectric permittivity effects in the detection of tree roots using ground-penetrating radar, Journal of Applied Geophysics, vol. 193: 104435.

De Figueiredo, J. et al., 2013. Automatic detection and imaging of diffraction points using pattern recognition, Geophysical Prospecting, vol. 61: 368–379.

Decker, L., Janson, X. & Fomel, S., 2014. Carbonate reservoir characterization using seismic diffraction imaging, Interpretation, vol. 3(1): SF21–SF30.

Decker, L., Merzlikin, D. & Fomel, S., 2017. Diffraction imaging and time-migration velocity analysis using oriented velocity continuation, Geophysics, vol. 82(2): U25–U35.

Delf, R. et al., 2022. Reanalysis of polythermal glacier thermal structure using radar diffraction focusing, Journal of Geophysical Research: Earth Surface, vol. 127(2): e2021JF006382.

Dell, S. & Gajewski, D., 2011. Common-reflection-surface-based workflow for diffraction imaging, Geophysics, vol. 76(5): S187–S195.

Fomel, S., 2002. Applications of plane-wave destruction filters, Geophysics, vol. 67(6): 1946–1960.

Fomel, S., Landa, E. & Taner, T., 2007. Postack velocity analisys by separation and imaging of seismic diffractions, Geophysics, vol. 72: U89–U94.

Fomel, S., Sava, P., Vlad, I., Liu, Y. & Bashkardin, V., 2013. Madagascar: open-source software project for multidimensional data analysis and reproducible computational experiments, Journal of Open Research Software.

Ford, J., Urgeles, R., Camerlenghi, A. & Gràcia, E., 2021. Seismic diffraction imaging to characterize mass-transport complexes: Examples from the Gulf of Cadiz, South West Iberian Margin, Journal of Geophysical Research: Solid Earth, vol. 126(3): e2020JB021474.

Gelius, L.-J., Tygel, M., Takahata, A. K., Asgedom, E. G. & Serrano, D. R., 2013. High-resolution imaging of diffractions — a window-steered MUSIC approach, Geophysics, vol. 78(6): S255–S264.

Grasmueck, M., Quintà, M. C., Pomar, K. & Eberli, G. P., 2013. Diffraction imaging of sub-vertical fractures and karst with full-resolution 3D Ground-Penetrating Radar, Geophysical Prospecting, vol. 61(5): 907–918.

Haidich, A.-B., 2010. Meta-analysis in medical research, Hippokratia, vol. 14(Suppl 1): 29.

Kanasewich, E. R. & Phadke, S. M., 1988. Imaging discontinuities on seismic sections, Geophysics, vol. 53: 334–345.

Khaidukov, V., Landa, E. & Moser, T. J., 2004. Diffraction imaging by focusing-defocusing: An outlook on seismic superresolution, Geophysics, vol. 69: 1478–1490.

Khoshnavaz, M. J., Bóna, A. & Urosevic, M., 2018. Post-stack diffraction imaging in vertical transverse isotropy media using non-hyperbolic moveout approximations, Geophysical Prospecting, vol. 66(2): 273–281.

Klem-Musatov, K., 1994. Theory of seismic diffractions, Society of Exploration Geophysicists.

Klokov, A. & Fomel, S., 2012. Separation and imaging of seismic diffractions using migrated dip-angle gathers, Geophysics, vol. 77(6): S131–S143.

Krey, T., 1952. The significance of diffraction in the investigation of faults, Geophysics, vol. 17: 843–858.

Kunz, B. F., 1960. Diffraction problems in fault interpretation, Geophysical Prospecting, vol. 8(3): 381–388.

Landa, E. & Keydar, S., 1998. Seismic monitoring of diffraction images for detection of local heterogeneities, Geophysics, vol. 63(3): 1093–1100.

Landa, E., Shtivelman, V. & Gelchinsky, B., 1987. A method for detection of diffracted waves on common-offset sections, Geophysical Prospecting, vol. 35: 359–374.

Li, C., Peng, S., Cui, X., Liu, Q. & Lin, P., 2022. Prestack diffraction separation by parameterizing the reflection local slope, Geophysics, vol. 87(2): S35–S44.

Li, C., Peng, S., Zhao, J. & Cui, X., 2020. Diffraction imaging using an adaptive phase filter, Geophysical Prospecting, vol. 68(1-Cost-Effective and Innovative Mineral Exploration Solutions): 164–177.

Li, C., Zhao, J., Peng, S. & Zhou, Y., 2021. Diffraction imaging using a mathematical morphological filter with a time-varying structuring element, Geophysics, vol. 86(3): S185–S196.

Lin, P., Peng, S., Zhao, J. & Cui, X., 2020. Diffraction separation and imaging using multichannel singular-spectrum analysis, Geophysics, vol. 85(1): V11–V24.

Maciel, S. & Biloti, R., 2020. A statistics-based descriptor for automatic classification of scatterers in seismic sections, Geophysics, vol. 85(5): O83–O96.

Merzlikin, D., Fomel, S. & Sen, M. K., 2019. Least-squares path-summation diffraction imaging using sparsity constraints, Geophysics, vol. 84(3): S187–S200.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. & Group*, P., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, Annals of internal medicine, vol. 151(4): 264–269.

Moser, T. J. & Howard, C. B., 2008. Diffraction imaging in depth, Geophysical Prospecting, vol. 56: 627–641.

Oesper, L., Merico, D., Isserlin, R. & Bader, G. D., 2011. WordCloud: a Cytoscape plugin to create a visual semantic summary of networks, Source code for biology and medicine, vol. 6(1): 7.

Reshef, M. & Landa, E., 2009. Post-stack velocity analisys in the dip angle domain using diffractions, Geophysical Prospecting, vol. 57: 811–821.

Santos, L. A. et al., 2020. Diffraction velocity analysis in a single-channel seismic survey in the Joetsu Basin, Geophysics, vol. 85(2): U47–U53.

Tranfield, D., Denyer, D. & Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review, British journal of management, vol. 14(3): 207–222.

Trorey, A. W., 1970. A simple theory for seismic diffractions, Geophysics, vol. 35: 762–784.

Tschannen, V., Ettrich, N., Delescluse, M. & Keuper, J., 2020. Detection of point scatterers using diffraction imaging and deep learning, Geophysical Prospecting, vol. 68(3): 830–844.

Tyiasning, S., Merzlikin, D., Cooke, D. & Fomel, S., 2016. A comparison of diffraction imaging to incoherence and curvature, The Leading Edge, vol. 35(1): 86–89.

Van Eck, N. & Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometrics, vol. 84(2): 523–538.

Červeny, V., 2001. Seismic Ray Theory, Cambridge University Press, Cambridge, UK.

Wang, B. et al., 2020. A Hilbert polarization imaging method with breakpoint diffracted wave in front of roadway, Journal of Applied Geophysics, vol. 177: 104032.

Yuan, H., Montazeri, M., Looms, M. C. & Nielsen, L., 2019. Diffraction imaging of ground-penetrating radar data, Geophysics, vol. 84(3): H1–H12.

Zhang, D., Fei, T. W., Tsingas, C. & Luo, Y., 2019. Efficient wave-equation-based diffraction imaging, Geophysics, vol. 84(5): S389–S399.

Zhao, J., Sun, X., Peng, S., Wei, W. & Liu, T., 2019a. Separating prestack diffractions with SVMF in the flattened shot domain, Journal of Geophysics and Engineering, vol. 16(2): 389–398.

Zhao, J., Yu, C., Peng, S. & Chen, Z., 2019b. Online dictionary learning method for extracting GPR diffractions, Journal of Geophysics and Engineering, vol. 16(6): 1116–1123.

Zhao, J., Yu, C., Peng, S. & Li, C., 2020. 3D diffraction imaging method using low-rank matrix decomposition, Geophysics, vol. 85(1): S1–S10.

Zhou, B., Hatherly, P. & Sun, W., 2017. Enhancing the detection of small coal structures by seismic diffraction imaging, International Journal of Coal Geology, vol. 178: 1–12.