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MODERN SEISMIC ACQUISITION METHODS BASED ON COMPRESSIVE SENSING, SIMULTANEOUS SOURCE RECORDING AND COMPRESSIVE RECONSTRUCTION

Abstract. Field seismic records are often incomplete due to missing data. Recovery of missing seismic data is necessary for the processing and interpretation of seismic data. As an effective solution to this problem, the paper considers reflection seismic methods for acquisition and processing based on Compressive seismic acquisition (CSA), compressive seismic reconstruction (CSR) and simultaneous source shooting (blended). The capabilities and geological problems that can be solved by each of the above methods are considered separately, as well as in the case of their complex application.

The factual basis of the conducted research was made up of a wide range of scientific publications, including the experimental results of the application of these methods.

The method of CSA is based on the principle of compressive sensing (CS), allows to carry out seismic survey with irregular indexing (arrangement of receiver and shot points) and is applicable to any geometry and design of survey. The fundamental concept behind CS is non-uniformly sampling the seismic data to let normally coherent aliased energy become incoherently sampled while maintaining the coherent sampling of seismic signal.

The method of reconstructing seismic data from insufficiently selected or missing traces is based on the extension to POCS (Projection Onto Convex Sets) interpolation method. The main idea of this approach differs significantly from

many previous interpolation methods, since it considers the reconstruction of seismic data as a task of obtaining high-resolution images in «computer vision» and directly indicates the hidden relationship between incomplete and complete seismic data, even with irregular indexing, according to a number of specific criteria and algorithms. Thus, compressive reconstruction of seismic data helps to convert incomplete input seismic data into complete ones.

With the simultaneous source shooting method several sources of seismic energy located at various shot points get triggered one after another within few seconds allowing to save enormous time resources by eliminating the wait time between source recordings.

All three methods described in this paper standout due to their focus on optimizing the production of field seismic surveys and improving image quality even with a smaller number of receiver stations for elastic vibrations and overlaying signal from various source points. Given the significant advantages of these methods, they can be considered as next generation reflection seismic technologies for operational effectiveness and high-resolution seismic recording.

Key words: seismic acquisition, compressive sensing, compressive reconstruction, simultaneous source shooting, deblending.

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КОМПРЕССИЯЛЫҚ ЗОНДТАУ, БІР МЕЗГІЛДЕ ТІРКЕУ ЖӘНЕ СЕЙСМИКАЛЫҚ ДЕРЕКТЕРДІ КОМПРЕССИЯЛЫҚ ҚАЛПЫНА КЕЛТІРУДІҢ НЕГІЗІНДЕГІ СЕЙСМИКАЛЫҚ БАРЛАУДЫҢ ҚАЗІРГІ ӘДІСТЕРІ

Аннотация. Далалық сейсмикалық жазбалар көбінесе деректердің болмауына байланысты толық емес. Жетіспейтін сейсмикалық деректерді қалпына келтіру сейсмикалық деректерді өңдеу және түсіндіру үшін қажет. Бұл мәселенің тиімді шешімі ретінде мақалада сығымдау сейсмикалық жинағына (CSA), сығымдау сейсмикалық қайта құруға (CSR) және бір уақытта көзді түсіруге (blended) негізделген шағылысу сейсмикасын жинау және өңдеу әдістері қарастырылады. Жоғарыда аталған әдістердің

әрқайсысы шеше алатын мүмкіндіктер мен геологиялық проблемалар бөлек, сондай-ақ оларды кешенді қолдану жағдайында қарастырылады.

Зерттеудің нақты негізін ғылыми жарияланымдардың кең спектрі, соның ішінде осы әдістерді қолданудың эксперименттік нәтижелері құрады. CSA әдісі компрессиялық зондтау (CS) принципіне негізделген, сейсмикалық барлауды дұрыс емес индекстеумен жүргізуге мүмкіндік береді (қабылдағыштың және түсіру нүктелерінің орналасуы) және кез келген геометрия мен түсіру конструкциясына қолданылады. CS-тің негізгі тұжырымдамасы сейсмикалық сигналдың когерентті үлгісін сақтай отырып, әдетте когерентті псевдонимдік энергияны герерентті емес үлгіні алуға мүмкіндік беретін сейсмикалық мәліметтердің біркелкі емес үлгісі болып табылады.

Жеткіліксіз таңдалған немесе жоқ трассалар бойынша сейсмикалық деректерді қалпына келтіру әдісі кеңейту интерполяциясы әдісіне негізделген POCS (дөңес жиындарға Проекция). Бұл тәсілдің негізгі идеясы алдыңғы интерполяцияның көптеген әдістерінен айтарлықтай ерекшеленеді, өйткені ол сейсмикалық деректерді қалпына келтіруді “компьютерлік көру” кезінде жоғары ажыратымдылықтағы кескіндерді алу міндеті ретінде қарастырады және толық емес сейсмикалық мәліметтер арасындағы жасырын қатынасты, тіпті тұрақты емес индекстеу кезінде бірқатар нақты критерийлер мен алгоритмдер көрсетеді. Осылайша, сейсмикалық деректерді сығылған қайта құру толық емес кіріс сейсмикалық деректерді толық деректерге айналдыруға көмектеседі.

Көзді бір уақытта түсіру әдісімен әр түрлі түсіру нүктелерінде орналасқан бірнеше сейсмикалық энергия көздері бірнеше секунд ішінде бірінен соң бірі іске қосылады, бұл бастапқы жазбалар арасындағы күту уақытын жою арқылы үлкен уақыт ресурстарын үнемдейді.

Осы мақалада сипатталған барлық үш әдіс далалық сейсмикалық барлау өндірісін оңтайландыруға және серпімді тербелістер мен көздің әртүрлі нүктелерінен сигнал беру үшін қабылдау станциялары аз болған кезде де кескін сапасын жақсартуға бағытталған. Осы әдістердің елеулі артықшылықтарын ескере отырып, оларды операциялық тиімділікті және жоғары ажыратымдылықтағы сейсмикалық жазбаны қамтамасыз ету үшін келесі буындағы сейсмикалық барлаудың шағылысу технологиясы ретінде қарастыруға болады.

Түйін сөздер: сейсмикалық барлау, компрессиялық зондтау, компрессиялық қайта құру, көзді бір уақытта түсіру, сұйылту.

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СОВРЕМЕННЫЕ МЕТОДЫ СЕЙСМОРАЗВЕДКИ НА ОСНОВЕ КОМПРЕССИОННОГО ЗОНДИРОВАНИЯ, ОДНОВРЕМЕННОЙ РЕГИСТРАЦИИ И КОМПРЕССИОННОЙ РЕКОНСТРУКЦИИ ДАННЫХ СЕЙСМОРАЗВЕДКИ

Аннотация. Полевые сейсмические записи часто бывают неполными из-за отсутствия некоторых данных. Восстановление пропущенных сейсмических данных необходимо для обработки и интерпретации сейсмических данных. В качестве эффективного решения данной задачи в статье рассмотрены методы сейсморазведки на отраженных волнах, получаемые и обрабатываемые по комплексу методов, состоящему из компрессионной сейсморазведки (Compressive Seismic Acquisition - CSA), компрессионной реконструкции данных сейсморазведки (Compressive Seismic Reconstruction - CSR) и метода одновременной регистрации нескольких источников (пунктов возбуждения). Рассмотрены возможности и решаемые геологические задачи каждого из вышеперечисленных методов по отдельности, а также в случае их комплексного применения.

Фактографический базис проведенных исследований составили широкий спектр научных публикаций, включая экспериментальные результаты применения этих методов.

Метод компрессионной сейсморазведки основан на принципе компрессионного зондирования, позволяют осуществить сейсмосъемку с нерегулярной индексацией (расстановкой пунктов приема и возбуждения) и применимы для любой геометрии и дизайна расстановки пунктов приема. Фундаментальная концепция, лежащая в основе компрессионного зондирования, заключается в неравномерной выборке сейсмических данных, чтобы позволить обычно когерентной наложенной энергии стать некогерентной выборкой, сохраняя при этом когерентную выборку сейсмического сигнала.

Метод реконструкции сейсмических данных по недостаточно выбранным или отсутствующим трассам базируется на методе интерполяции POCS. Основная идея такого подхода существенно отличается от многих предыдущих методов интерполяции, поскольку рассматривает реконструк-

цию сейсмических данных как задачу получения изображений высокого разрешения в «компьютерном зрении» и напрямую указывает на скрытую связь между неполными и полными сейсмическими данными по ряду специфических критериев и алгоритмов. Таким образом, компрессионная реконструкция данных сейсморазведки помогает преобразовывать неполные входные сейсмические данные в полные.

В методе одновременной регистрации сигнала группы пунктов возбуждения, расположенные в разных точках площади наблюдений, срабатывают один за другим в интервале первых секунд, что позволяет сэкономить значительные временные ресурсы за счет устранения времени ожидания между записью пунктов возбуждения.

Все три метода, описанные в этой статье, отличаются направленностью на оптимизацию производства полевых сейсморазведочных работ и улучшение качества изображений даже при использовании меньшего количества регистрирующих пунктов приема упругих колебаний и наложения сигнала с разных пунктов возбуждения. Учитывая значительные преимущества указанных методов, их можно рассматривать как технологии сейсморазведки на отраженных волнах следующего поколения и для получения сейсмической записи высокого разрешения.

Ключевые слова: сейсморазведка, компрессионная сейсморазведка, компрессионная реконструкция данных сейсморазведки, метод одновременной регистрацией нескольких источников.

Introduction. The seismic acquisition is one of key geophysical surveys to measure the earth's properties with certain benefits that make it the most demanded and advanced among other methods in the upstream oil and gas - it produces detailed images of the subsurface, in cases can directly detect hydrocarbons, and used to delineate stratigraphy. Nevertheless, modern-day exploration industry demands even more advanced and efficient technologies to look deeper into the subsurface and understand formations with higher complexity, in terms of structure, stratigraphy, mineral and fluid content, saturation type, etc. There are several key factors that impact the quality of raw seismic data including survey design, source of energy, recording equipment and others. Present high density seismic acquisition designs are attractive because they provide high resolution anti-aliased seismic data which is particularly helpful for imaging and inversion. Although such acquisition designs provide the best imaging quality, the costs of conventional acquisition rise as trace density increase, especially when the target object is deeper and has a complexity due to shape, structure, lithology and reservoir properties. Furthermore, it is common that acquired field seismic data has uneven coverage due to various surface obstacles and acquisition issues, often due to infrastructure safety offsets, permitting limitations, landscape and natural challenges etc. This paper provides an overview on the modern seismic survey methods, such as Compressive seismic acquisition (CSA), compressive seismic reconstruction (CSR) and simultaneous source shooting (blended) seismic acquisition.

Compressive seismic acquisition (CSA). The review of various modern seismic survey methods and their comparison to conventional methods revealed a competitive advantage of the Compressive seismic acquisition (CSA) design. This method is based on compressive sensing (CS) theory which is mathematically proven to diminish the acquisition of unnecessary information and reconstruct the under-sampled data with a high degree of accuracy (Candès et al., 2006; Donoho, 2006). The basic principle of CS is to sample the wavefield irregularly so that the spatial aliasing patterns are rendered incoherent and faded, which allows inversion solvers to predict the coherent signal. Figure 1 illustrates how significantly the amount of receiver and source stations can be reduced from the survey design when CSA approach is applied. Noticeably this approach increases the overall seismic productivity, as less equipment will be deployed in the field, while providing full set of traces for interpretation after special processing is applied.

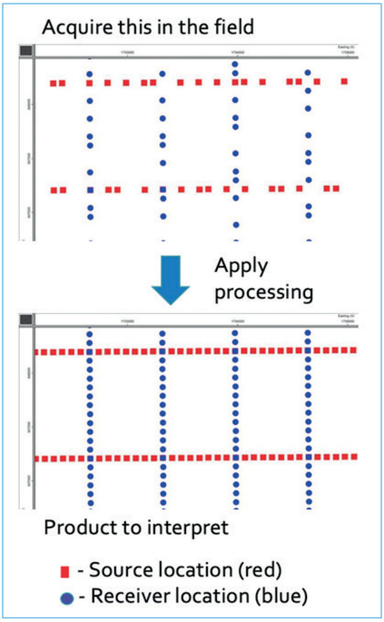

Figure 1. Basic illustration of Compressive seismic acquisition (CSA) to increase the overall seismic productivity by non-uniformly sampling the earth

Compressive Seismic (CS) is a relatively new approach to seismic data acquisitions first introduced by Hennenfent and Herrmann (Hennenfent and Herrmann, 2008). It was somewhat known at a theoretical level before, but applying it in real life surveys was problematic. Large-scale seismic surveys with compressive sensing (CS) have been made affordable recently due to the optimizations in CS algorithms and increasing computation power needed for seismic signal processing (Mosher, 2014; Li, 2013).

As mentioned above, the fundamental concept behind CS is to non-uniformly sample the seismic data to let normally coherent aliased energy become incoherently sampled while maintaining the coherent sampling of seismic signal. For example, CS technology provides the ability to acquire the same fold for significantly less equipment and costs or more fold on the same bin size using the same costs and equipment.

There was a test of Compressive Sensing undertaken on a recent explosive-source based 3D seismic survey to evaluate the technology and its ability to save costs and/or increase resolution (Jiang, 2018). Two scenarios assessed: economically efficient "cost" option with reduced number of traces and conventional regularly gridded "base" option. Basically, to test the genuineness of the CSA design a noteworthy amount of receiver and source stations were intentionally removed and later reconstructed during pre-processing with CSR.

Figure 2 is an example of the before and after reconstruction of "cost" shots and comparison with "base". In figures 2a and 2b, the left shot had missing receivers, and the right shot a whole missing shot. The difference plot (Figure 2d) indicates that "cost" CS-R is comparable to "base" case, with most reflection energy preserved and incoherent noise attenuated. In other words, the primary signal of interest was not negatively impacted due to reduction of receiver and shot points, but even improved due to less background noise.

As per conclusion of this field study the reconstructed trace does not exactly recreate the acquired field data; rather it recreates the most coherent signal but cannot recreate the incoherent components such as background noise that occurs during a survey. This causes some noticeable variations between real data and reconstructed data.

It is observed that compressive seismic acquisition (CSA) can considerably reduce time and costs when combined with seismic de-blending and especially compressive seismic reconstruction (CSR).

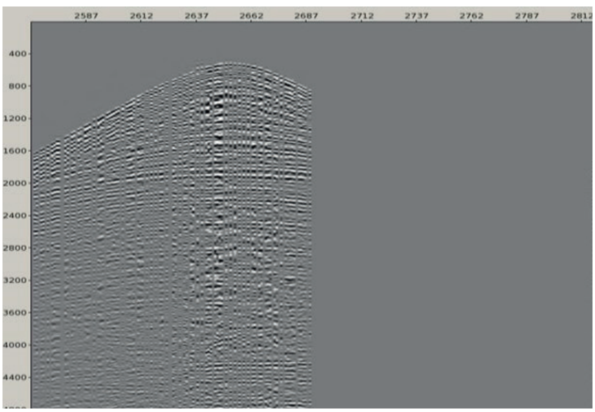

Figure 2a. Shots of "cost" survey: the left shot has missing receivers, and the right shot shows a whole missing shot

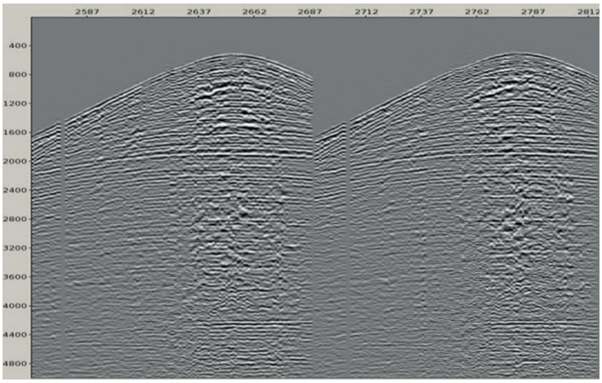

Figure 2b. Shots of "cost" survey after applying CS-R: missing receivers in the left shot were reconstructed, and a whole missing shot was reconstructed in the right shot

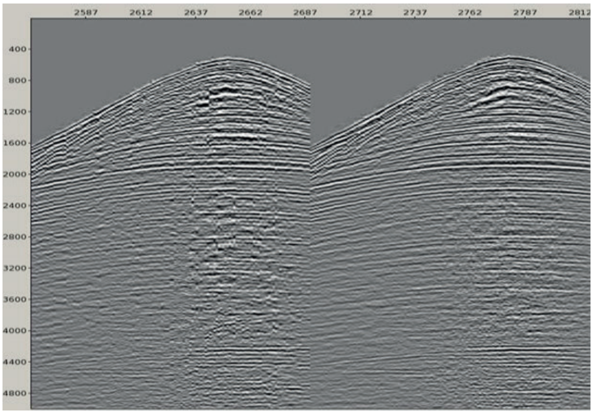

Figure 2c. Shots of "base" survey using conventional design, i.e. not applying CS and not skipping source/receiver stations

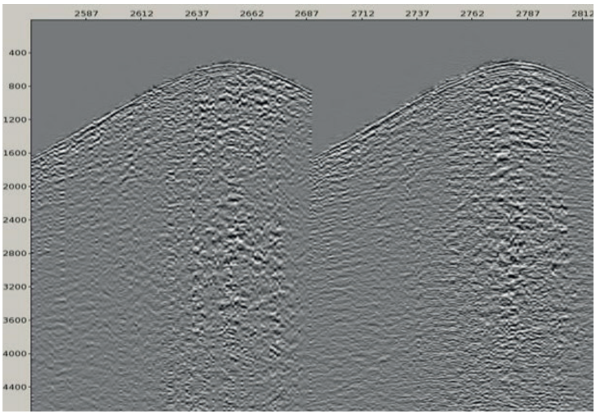

Figure 2d. Shots difference of "base" survey (Fig.2c) and "cost" survey CS-R (Fig.2b). (Seismic Data Courtesy of TGS)

Compressive seismic reconstruction (CSR). In the past few years, the economic drivers and rapidly growing data volumes increased the value of compressive seismic (CS) method in the oil and gas industry. Several field trials and full-scale production acquisitions utilizing CS technology have been conducted by oil companies (Mosher, 2014; Li, 2013). An essential portion of CS process requires a reconstruction step to recreate the missing trace data in the input data volume.

By utilizing the coherency of seismic signals in sparseness promoting domains, seismic records compressed to lower than Nyquist rate can be recovered near perfectly with sparse inversion (Duarte, 2005; Donoho, 2006). Many methods have been studied extensively, such as sparse inversion (Candes, 2008) for Basis Pursuit De-Noise problem (BPDN), Minimum Weighted Norm Interpolation (MWNI) (Liu, 2004), Anti-Leakage Fourier Transform (ALFT) (Xu, 2010), and Projection Onto Convex Sets (POCS) (Stasinski, 2000 and 2002; Abma, 2006). Each CSR method has its own advantages and drawbacks: sparse inversion is not easy to set up the parameters and converges slowly. MWNI tends to produce linear artifacts if not set up carefully. ALFT's performance can degrade for data with sampling showing limited irregularity. POCS requires input on regular grids where data is jittered under-sampled (Hennenfent, 2008; Mosher, 2012).

An extension to POCS method which was discussed in details in 2017, enables to avoid its main problem and make it possible to be used for CSA in production. This extension to POCS (EPOCS) by incorporating an interpolator is proposed to fundamentally expand its capability to do compressive seismic reconstruction in production from arbitrarily irregular under-sampled input. The proposed CSR-EPOCS is free from a predefined nominal grid and capable of reconstructing input data to any given grids. Jiang (2017) provides 2D examples representing its superior signal-to-noise ratio and amplitude conserving capability compared to traditional POCS. Also, the real 3D land data examples demonstrate its effectiveness and potential to improve shallow image under acquisition gaps. For instance, the above field trial example (Figure 2b) used CSR workflow with Extended-POCS as the reconstruction method. Another CS processing tests were run on blended vibroseis data from a recent very high-density wide azimuth land seismic survey from Oman and proved its credibility (Jiang et al, 2019). For example, it is observed that CS reconstruction reduces aliasing of ground roll noise and facilitates its removal, and the comparison of the final migrated stacks shows that the CSR image is generally comparable to Full data image, even though the CSR data set had just 25% of the trace density of the Full data set.

Figure 3 shows CSR example for a 3D land data using the CSR-EPOCS method. At the time slices raw data has random missing data across the whole area with acquisition gaps. To compare, the sparse Tau-P based interpolation which is data regularization algorithm combining a sparse $\tau - p$ inversion scheme with low-rank optimization was tested. The sparse Tau-P improves the image, but there are obvious acquisition footprints and noise. The CSR-EPOCS, with or without anti-alias FK mask, provides a much better reconstruction. It has higher signal to noise ratio, less footprints from irregular data and clearer geological structures. The inline cross-section close to the acquisition gaps show under-migrated diffractions, especially at the near surface. CSR makes the events more continuous, reduces diffraction noise from the missing traces, and recovers the amplitude.

It is worth to mention that this CSR with extended POCS (CSR-EPOCS) method expands the usability of POCS and can be used with any chosen transform and thresholding model.

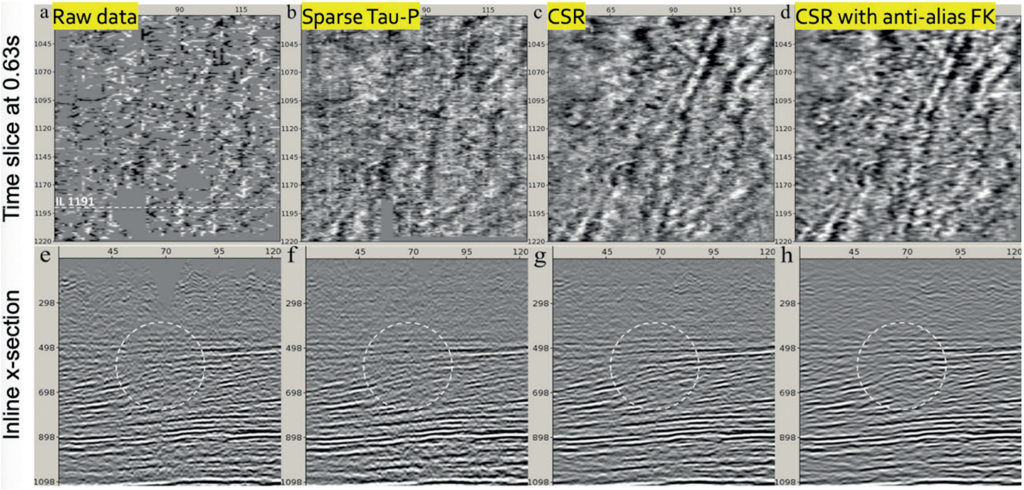

Figure 3. Land data example of reconstruction with different methods. From left to right, the first row are the time slices (0.63s) of one common offset gather (1500ft) for (a) raw data, (b) sparse Tau-P, (c) CSR, and (d) CSR with anti-alias FK mask, respectively; and the second row are one inline of stack images near holes for (e) raw data, (f) sparse Tau-P, (g) CSR, and (h) CSR with anti-alias FK mask, respectively

Simultaneous source shooting acquisition. Among variety of approaches aimed to optimize seismic acquisition and improve the imaging capabilities the simultaneous source shooting (or blended) seismic acquisition stands out; especially as computing resources advance and the need for economic efficiency increase. Many studies and tests have been done for independent simultaneous source seismic acquisition, which is a type of high-efficiency survey with multiple sources recording in parallel. Essentially, several sources of seismic energy located at various shot points get triggered one after another with few seconds delay. This approach can save enormous time resources, and consequently bring cost efficiency by eliminating wait time between source recordings. Since there will be several source signals overlapping each other the deblending process, in other words removing blending interference from other sources, needs to be done before processing and imaging. In combination with CS acquisition and CS reconstruction methods the blended seismic acquisition can be considered as the most applicable one for high-efficiency seismic surveys.

Through the last fifteen years the blended acquisition concept was actively developing and maturing. There are many papers dedicated to this technology. For example, Delphi consortium started to formularize the inversion problem from blended acquisition in matrix format (Berkhout, 2008), which was studied and tested in details later (Mahdad, 2011); BP pioneered the advancement and commercialization of the deblending inversion by a series of field trials (Abma and Yan, 2009; Alexander et al., 2013; Zhang et al., 2013; Abma, 2014, 2015). The deblending methods can be viewed from two sides: one treats the blending interference as noise and uses a denoise method, and the other treats the blending interference as signal from another source, and then uses an inversion method.

Figures 4 and 5 show an example of blended shot from the case-study survey in the deep-water Argentina Basin (Jiang, 2021). The B1 and C1 indicate direct arrivals from the first and the following shot accordingly, while B2 and C2 correspond to water bottom reflections (Figure 4).

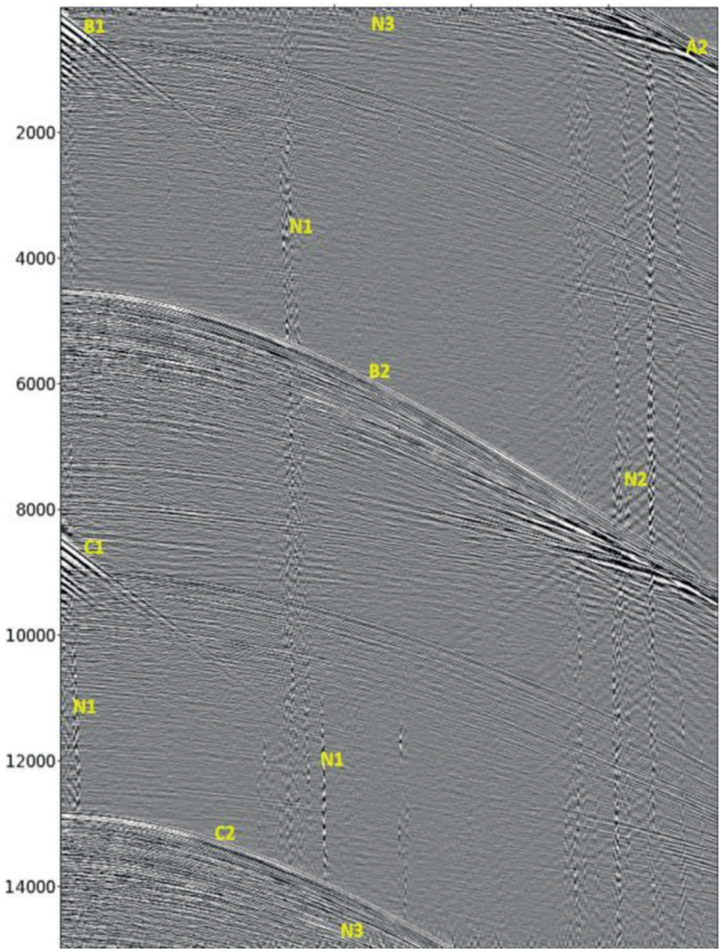

Figure 4. Sample shot gather with successive shots self-blending. The traces start at time zero of the current shot, with a length of 15sec and 2ms sampling rate. The marked events are: A2: previous shot water bottom; B1: current shot direct arrival; B2: current shot water bottom; C1: next shot direct arrival; C2: next shot water bottom; N1: swell noise; N2: cable strike noise; N3: trace edge noise (Jiang, 2021)

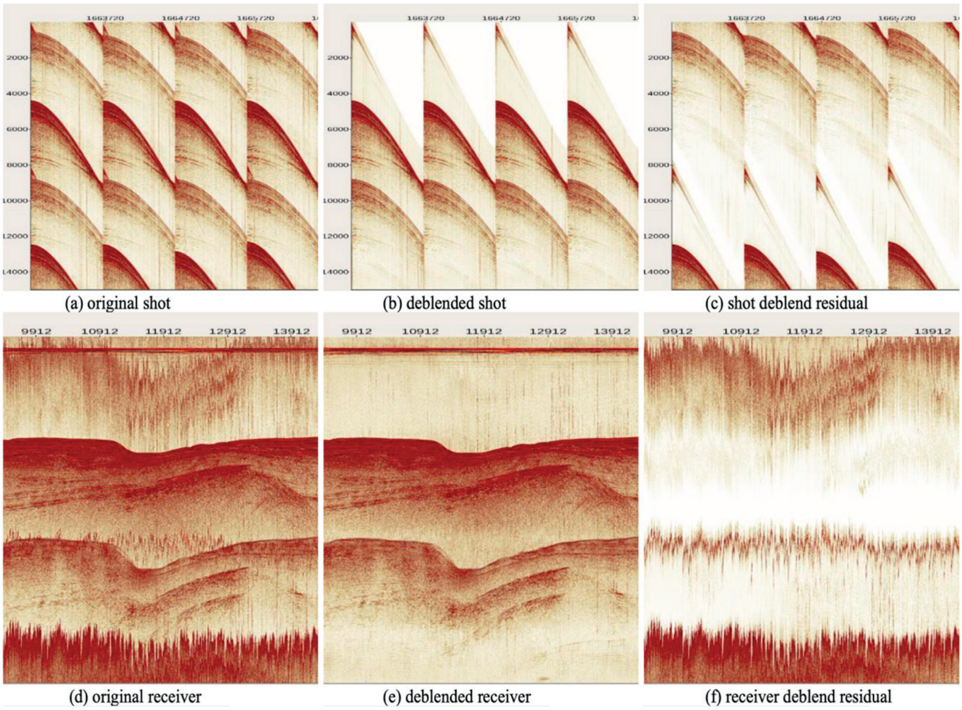

Figure 5. Results and QC for the deblending of the 2D marine dataset with self-blending. All the plots show the whole length of 15sec. (a)(b)(c) are the input/deblend/residual for shot domain; (d)(e)(f) are the input/deblend/residual for receiver domain (Jiang, 2021)

Examples shown above are from a deblending study of a common marine 2D survey with single-source self-interference. Author states that this survey was challenging to work with because of the low dimensionality, spliced shots with time error and edge artifact, and no special shot time schedule. Even with such data the inversion-based deblending with EPOCS kernel showed to be effective in solving this problem and produced a satisfactory result.

Discussion. It is well known that seismic image quality greatly depends on survey design, source and receiver parameters, signal-to-noise level and data processing flow. In search of efficient high-density seismic acquisition methods to study deep-lying and complex structured oil and gas formations this paper reviews and demonstrates the Compressive Sensing (CS) concept and simultaneous source recording method as an optimal solution. Given that CS approach supports irregular grid and flexible in dealing with "no permit" zones, there could be any type of 3D design, from orthogonal to random, implemented.

It worth to mention that Compressive seismic acquisition and processing getting a vast amount of attention in the seismic industry and are often regarded as the next generation for cost-effectiveness.

Conclusions. The combination of Compressive seismic acquisition (CSA) along with Compressive seismic reconstruction with extended POCS (CSR-EPOCS) and blended seismic acquisition method can be considered as an optimal combination for seismic acquisition design. These were tested at various field trials, separately and in combination, and proved to be an accurate and fast algorithm suitable for industry-scale data processing.

In general, seismic survey takes a huge portion in exploration and field development for oil and gas industry, therefore the benefit of above methods to cut cost (with less equipment required, blended sources and faster acquisitions) and increase resolution makes them even more admired, and impacts the business decision in new seismic acquisitions.

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