Preface to the Focus Section on Nonexplosive Source Monitoring and Imaging

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Seismic waves generated by a natural or an artificial source provide a direct means to probe the Earth's interior, and seismic tomography and migration are techniques developed for imaging Earth's 3D velocity structure and internal boundaries (e.g., Gray, 2001; Rawlinson *et al.*, 2010). The resolution of seismic imaging depends mainly on the wavelength of seismic waves. In general, seismic waves generated by natural sources, such as earthquakes, feature larger amplitude and longer wavelength as compared with those produced by artificial sources. Hence, passive-source seismic waves can penetrate deeper into the Earth and have consequently served as the primary source to decipher the structure and composition of the Earth's deep interior, that is, the mantle and core. The long wavelength of passive-source seismic waves, on the other hand, places a great limitation on their capability to resolve fine-scale structures. Active sources are thus preferred when high-resolution subsurface images are required for the purposes of resource exploration and engineering site characterization.

Depending on the targeting depth, seismologists invented various types of artificial sources, for example, hammers, vibrators and explosives for onshore acquisition and airguns for offshore acquisition. Among these different sources, explosive sources are known to have the capacity for generating large-amplitude, far-reaching and simple-shaped seismic waves and are thereby widely used by the petroleum industry to image sedimentary structure and by the research community to study the crust and the uppermost mantle (e.g., Li and Mooney, 1998; Zelt *et al.*, 2006). Meanwhile, airguns have become an effective source for producing acoustic waves in marine environments. In the United States, marine seismic acquisition and exploration dominated the oil industry for many years before the shale revolution. Airguns are also widely used by academic researchers to investigate active and passive margins, with both offshore and onshore recordings (e.g., Okaya *et al.*, 2002; Bezada *et al.*, 2010). In general, airguns are considered to be more environmentally friendly and controllable sources as compared to chemical explosions.

In recent years, time-lapse seismic imaging (4D) has received wide attention because accurate imaging of the evolving subsurface structure has significant applications in disaster reduction, resource exploration, and environmental monitoring (e.g., Yamamura *et al.*, 2003; Niu *et al.*, 2008). One particularly interesting area to seismologists is the monitoring of the time-varying stress field associated with major earthquakes and magmatic eruptions through the detection of temporal changes in the crustal velocity at seismogenic and volcanogenic depths (e.g., Brenguier, Campillo, *et al.*, 2008; Brenguier, Shapiro, *et al.*, 2008). Such a monitoring system would perhaps be the single most important means of understanding the physical processes and stress changes that lead to earthquake rupture and volcanic eruption.

A critical component in accurate 4D monitoring velocity changes for seismic and magmatic applications is the development of a source that is particularly well suited for this application. Such a source needs to be sufficiently powerful to propagate the tens of kilometers needed for fault-zone monitoring, sufficiently repeatable to minimize temporal changes in the source characteristics and in the immediate source environment, sufficiently durable to operate continuously for long periods of time, and connected to a sufficiently precise acquisition system to measure the minute changes in travel-time and waveform similarities.

The past decade witnessed significant progress in controlled source technology, data acquisition, and analyses. In particular, scientists from the China Earthquake Administration made tremendous efforts to reinvent an airgun as a highly repeatable and powerful source (Chen *et al.*, 2007; Wang *et al.*, 2012). Numerous tests with large-volume airgun sources have been conducted inside natural and man-made lakes, rivers, and even boreholes. Several Fixed Airgun Signal Transmission Stations (FASTS) have been set up at different parts of continental China to monitor structural changes along active faults and dams (Chen *et al.*, 2007).

In this *SRL* focus section, we publish six articles that include investigations on the optimum deployment depth, source signature, and data processing of the new type of inland airgun, as well as several case studies of subsurface imaging and monitoring using temporarily deployed inland airgun sources and permanent FASTS sites. Wei *et al.* (2018) investigated how different placement depths of the airgun source affect the source signature using a FASTS site near the Qilian Mountain in Gansu Province, China. They found that both the amplitude and the dominant frequency of the airgun signals increase with increasing placement depth, and there is an optimum deployment depth at which the airgun signal radiating from the source has the highest amplitude and broadest frequency band. Wang *et al.* (2018) compared seismic records in southwest China from closely located airgun shots, a chemical explosion, and a small earthquake that have approximately the same magnitude, M_L 0.7. They found that the airgun signals have the lowest frequency content and thus can reach the farthest distance, ~40 km for a single shot. With 20 times of stacking, the airgun signals can be detected as far as 150 km, which can be readily used in studying deep crustal structures.

Tian *et al.* (2018) conducted a travel-time tomography study using 3D wide-angle reflection/refraction experimental data acquired with airgun shots detonated inside the Anhui section of the Yangtze River in central China. They found that the

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first arrival can be easily picked up to 160 km from the stacked waveforms of repetitive shots. With more than 2000 picks of first arrival at several short-period arrays deployed in an area of 200 × 150 km around the Yangtze River, they obtained a 3D *P*-wave velocity model with a reasonably good lateral resolution up to a depth of 10 km. Their results suggest that there is a very good correlation between high-velocity anomalies and the ore deposits known in the area. Meanwhile, She *et al.* (2018) inverted the surface-wave dispersion data extracted from the same dataset of Tian *et al.* (2018) and constructed a 3D *S*-wave velocity model of the area. They again confirmed the good correlation between velocity structure and ore deposit distribution.

Yang *et al.* (2018) detected large velocity variations ranging from 5% to 20% from seismic records of repeated shots of an airgun that was creatively installed in a downhole near the Xiaojiang fault zone in the Yunnan Province, southwest China. They compared the observed velocity variations with changes in groundwater level and found a good agreement between the two sequences, suggesting that the seismic-velocity structure of the shallow layer is very sensitive to the effective stress and fluid saturation. Olivier *et al.* (2018) introduced a novel supervised machine-learning technique to separate a weak active source signal from coherent background noises. They showed that the method was able to extract a weak active signal recorded by a sensor that is located more than 1 km away from the source. Regular stacking and seismic interferometry technique were unable to detect this signal.

In summary, the first five papers published in this special section focus on different aspects of the inland airgun source developed in China, which is a promising controlled source that has long been sought by the seismology community. The novel technique discussed in the sixth paper, on the other hand, demonstrates that seismologists are ready to add the state-of-the-art machine-learning technique to their evolving toolbox.

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