Structure of the Mt Isa region from seismic ambient noise tomography

E. SAYGIN1*, H. McQUEEN1, L. J. HUTTON2, B. L. N. KENNETT1 AND G. LISTER1

1Research School of Earth Sciences, The Australian National University, Canberra ACT 0200, Australia.
2Geological Survey of Queensland, Department of Natural Resources and Mines, Level 10, 119 Charlotte Street, Brisbane, QLD 4002, 4000 Australia.

We use seismic tomography, exploiting group velocities derived from ambient noise, to delineate the crustal structure beneath Mt Isa and the surrounding blocks and basins. The depth extent of the blocks can be traced into the mid-crust and the spatial extent of the associated velocity anomalies mapped over an area of approximately 500 km by 500 km. The Proterozoic Mt Isa block is imaged as a region of elevated seismic velocities comparable to the Yilgarn craton in Western Australia, while the surrounding basins have relatively low velocities. Seismic velocity anomalies display correlations with the regional Bouguer gravity data and with high crustal temperatures in the region. There are a number of isolated low-velocity anomalies under the Millungera basin that suggest either previously unknown thermal anomalies or zones with high permeability, which can also produce lowered velocities.

KEYWORDS: Mt Isa, Australia, lithosphere, Proterozoic, seismology, ambient seismic noise tomography.

INTRODUCTION

Seismic tomography exploiting ambient noise is a relatively new technique, which uses continuously recorded seismic noise propagating through the Earth to map variations in crustal seismic velocity associated with structural and thermal contrasts. The main component of the ambient noise field of the Earth is generated from ocean-ground coupling (Longuet-Higgins 1950), which spreads out from ocean storm centres and is continuously recorded at seismic stations; excitation of noise can also occur at the edge of the continental shelf. By cross-correlating the seismic noise simultaneously recorded at two different stations, it is in general possible to retrieve a deterministic wavelet (e.g. Shapiro & Campillo 2004). This wavelet, or Green’s function, represents the seismic response as if one of the stations is acting as a source and the other as a receiver. Green’s function between source and receiver carries the signature of the seismic wave speed structure between the stations. With a dense network it is possible to extract many Green’s functions by cross-correlations between all pairs of stations. The interrogation travel times for waves on the multiple paths can then be employed in a tomographic inversion to map the seismic wave speed perturbations across the network.

Ambient seismic techniques have the merit that they allow effective imaging of regional geological structures using just passive seismic recordings. Following the pioneering work of Shapiro & Campillo (2004) and Shapiro et al. (2005) in California, many other studies have been conducted to image the Earth at various scales by using seismic ambient noise correlation. The technique has been applied to areas in the USA (Sabra et al. 2005; Liang & Langston 2008; Yang et al. 2011), New Zealand (Lin et al. 2007; Behr et al. 2010), Australia (Saygin & Kennett 2010, 2012; Arroucau et al. 2010; Young et al. 2011) and China (Yang et al. 2010; Zhou et al. 2012).

Over the last decade, the seismic structure of the Australian lithosphere has been investigated with increasing resolution owing to the expanding instrumentation coverage of the continent. Tomographic studies have been conducted by using seismic surface waves from earthquakes (Zielhuis & van der Hilst 1990; Simons et al. 1999; Debayle & Kennett 2000a, b; Yoshizawa & Kennett 2004; Fishwick et al. 2004, 2006), seismic attenuation (Kennett & Abdullah 2011), seismic anisotropy (Heintz & Kennett 2005, 2006) and seismic body wave tomography (Pearson et al. 2006; Rawlinson & Fishwick 2011) have been carried out using seismic body waves. Teleseismic studies using sources at the surrounding plate boundaries provide good coverage for lithospheric tomography. However, the relatively low seismicity of the Australian continent limits the extent of local tomographic studies using body waves. For Australia, seismic ambient noise tomography fills an important gap revealing shallower structure than conventional methods both at the continental scale (Saygin & Kennett 2010, 2012) and more locally, as in the work of Young et al. (2011) for Tasmania. The design of a network of portable stations provides direct control on the distribution of the set of propagation paths between the stations. Along each path, surface
wave information from Green’s function gives penetration to a range of depths. Hence, the shallow crust can be imaged without the need for earthquakes as a probing source.

In this study, we exploit the results from portable seismic instrumentation deployed in the Mt Isa region between 2009 and 2011, together with permanent seismic stations and other portable stations (Figure 1). Surface wave dispersion information for 800 paths crossing the Mt Isa region was extracted from the cross-correlograms of station pairs, and used to image the variations in seismic wavespeeds. The seismic results identify

![Figure 1](image_url)

*Figure 1* Surface geology of the region (Raymond et al. 2010). Seismic networks used in this study are marked with triangles.
significant geological boundaries that can be followed to depth. Patches of relatively low seismic wavespeed suggest rocks that have relatively low density, because of their composition, or because they are porous and/or permeable sediments. Volumes of fractured rock are unlikely to be resolved at the scale of this experiment. Note that the movement of fluids means that such permeable zones should have localised high geothermal gradients.

GEOLOGY

The Mt Isa region contains several geological terranes that were formed at the edge of the Northern Australian Craton as the result of tectonic activity during early to mid-Proterozoic orogeny (Betts & Giles 2006; Betts et al. 2006). The Mt Isa region is one of the best-exposed Paleo-proterozoic terranes on Earth. The so-called metal orogeny began with the Barramundi event (1.86 Ga) correlated globally (Hou et al. 2008) with the Svecofenian of Europe or the Hudsonian of Northern America (Etheridge et al. 1987). Large-scale crustal extension sporadically afflicted this terrane, up until ca 1.6 Ga, producing basins in which much of Australia’s base metal mineral wealth accumulated. These basins were inverted by approximately east–west compression that commenced at ca 1.58 Ga, and produced regionally developed fold and thrust belts as part of the Isan Orogeny (Betts et al. 2006). Regional low-pressure high-temperature metamorphism produced large extents of medium- to high-grade crystalline rocks. Later wrench faulting dissected these terranes producing the map patterns we observe today, with three major north–south oriented fold belts.

The Proterozoic Mt Isa inlier is divided into three major north–south oriented fold belts (Blake 1987; O’Dea et al. 1997), with the Kalkadoon-Leichhardt Belt in the centre, and the Western and Eastern fold belts on either side. The Mt Isa inlier is surrounded by two major basin structures: the Georgina Basin and the Eromanga Basin. The Georgina Basin was formed by disruption of the Centralian Superbasin during the Petermann Ranges Orogeny with central uplift, and associated thrusts at 600–540 Ma, followed by mid-Carboniferous tectonism (320 Ma) (Walter et al. 1995).

The Eromanga Basin along with the Cooper Basin, host the largest onshore oil and gas fields in Queensland (Reynolds et al. 2006). The Mt Isa domain itself hosts a number of large mineral deposits including sulfide Pb–Zn–Ag, Cu, Broken Hill-type Ag–Pb–Zn and iron-oxide–Cu–Au type mineralisation (Betts et al. 2006; Blenkinsop et al. 2008), and is one of the world’s leading producers of Zn, Pb, Cu and Ag (Hutton et al. 2012).

DATA

Between 2009 and 2011, the MINQ seismic array was operated in the Mt Isa region, spanning from the Georgina to Eromanga basins, by the Research School of Earth Sciences of ANU as an AuScope project, with a total of 49 stations (see Figure 1). A set of 33 seismic

recorders with Lennartz LE-3Dlite short-period 3 component sensors were used, and progressively redeployed eastward to increase the spatial coverage. Each station was run continuously with a sampling rate of 25 Hz or higher. Also, nearby stations with short-period and broadband sensors from the permanent IRIS and Geoscience Australia networks and the BILBY temporary deployment from ANU were used to increase the spatial coverage of the study.

Before cross-correlating recorded ambient seismic noise, instrument corrections were applied to every record to equalise the sensor responses. Where available, tabulated instrumental responses were used, but otherwise the nominal response for each sensor type was employed. Daily volumes of uncompressed data were created for each component recorded at a seismic station. The cross-correlations were carried out in the frequency domain to reduce the computational cost (see Appendix A). For the cross-correlations between a pair of stations, a 4 h window was used with 1 h overlap. The calculated correlograms for each of the available 4 h window were stacked to create a stable estimate of Green’s function for this station pair. This procedure was repeated for all of the other pairs of stations. Cross-correlation of the seismic noise recorded at these various stations produced over 800 individual high quality Green’s functions. These Green’s functions were then processed to extract group velocity information for each path as a function of frequency. The path information was then used to produce wavespeed variation maps as a function of frequency using tomographic imaging.

METHOD

The method of cross-correlation of seismic ambient noise has recently emerged in seismology as an alternative technique to imaging carried out with traditional sources, e.g. earthquakes, explosions, etc. The control on the experiment configuration in this method gives freedom comparable to active source seismic surveys for a fraction of the cost (e.g. Young et al. 2011).

Although, in principle, Green’s function would include all aspects of the seismic wave propagation between the pair of stations, the stable part is the contribution from seismic surface waves (e.g. Shapiro et al. 2005). Rayleigh waves can be extracted from stacked cross-correlations of vertical and radial component pairs, and often Love waves can also be extracted from the cross-correlations of the transverse component of the noise field. In this study, we will only use the Rayleigh wave portion of Green’s function.

In Figure 2, we show the estimates of the interstation Green’s functions extracted from the ambient noise for propagation paths in two different tectonic domains. In the cratonic Mt Isa area, surface waves propagate much faster than in the Carpentaria sedimentary basin leading to systematically earlier arrivals (see Figure 2a, b). We exploit the differences in the seismic wave characteristics for different paths, by measuring the group velocities for each path at a number of periods. The group velocity of a surface wave is the propagation speed of the envelope of the wave packet.
AMBIENT SEISMIC NOISE TOMOGRAPHY

After measuring the group velocities at different periods for the Rayleigh wave part of Green’s functions between available stations, a tomographic problem is constructed to map the spatial variations in velocity for every selected period. We use a similar approach to that employed by Saygin & Kennett (2010). We start with the Fast Marching Method (FMM; Rawlinson & Sambridge 2004) to trace seismic wavefronts propagating in the heterogeneous media, and calculate the travel times for the wavefronts for a given input model. The second stage of the tomographic inversion is to minimise the difference between the modelled traveltimes and the observed ones, for which a subspace technique is employed (Kennett et al. 1988).

Seismic tomographic inversion is applied to group transit times for the suite of paths at a selection of periods between 1 and 10 s. Surface waves propagating with different periods sample different parts of Earth, and in general, surface waves at longer periods sample deeper parts of Earth compared with shorter periods. We display images of the group wavespeeds as a function of period in Figure 3. Where variations in the phase and group wavespeeds are weak, the local dispersion properties as a function of period can be interpreted in terms of 1-D structure beneath the point (Woodhouse 1974). It is possible to perform a similar analysis using phase velocities of the waves. This would produce a complementary set of images sampling the region in a slightly different ways. However, the approximations used in the extraction of the phase velocity of surface waves break down in regions of complex structure such as this, and we have therefore used only the more robust group velocity analysis.

In the Mt Isa region, we have very strong variations in properties, and unfortunately, the local dispersion relation cannot be exploited to extract shear wavespeed structure. However, we can use the approximate correspondence of period and depth in kilometres to obtain an indication of the depth extent of features. In areas with sedimentary cover, the sensitivity is pulled up towards the surface (see Figure A2), and so the images in Figure 3 cannot be interpreted directly as a depth slice.

Because of their finite frequency, the surface waves sample a zone around the nominal propagation path. A convenient estimate of the extent of this sampling is provided by the influence zone of Yoshizawa & Kennett (2002), which corresponds to 1/6 of the first Fresnel zone. Figure A3 presents spatial resolution tests for the Mt Isa region for periods of 3 s and 8 s to indicate the reliability of the images. In the central portion with a high density of stations, structures are well resolved and there is a good recovery of the amplitude of the imposed anomalies. Because of the distribution of the available seismic

**Figure 2** Extracted Green’s functions from two different geological regions: (a) Mt Isa, (b) Carpentaria Basin. Dashed lines show the expected arrival time for a reference velocity of 3.2 km/s. Earlier arrivals with respect to these lines indicate faster seismic velocities. Waveforms are filtered between 0.1 and 0.3 Hz and normalised to unity. Notice the systematic difference in arrival times of Green’s functions in the two different domains.
stations, the path density and spatial coverage decrease drastically towards the edges where only isolated paths are available. This uneven distribution of available propagation paths causes smearing and artefacts in the mapped seismic velocity perturbation such as in Figure 3 (south of 21°) for periods from 3 to 8 s. These spurious structures are not included in the interpretation.

RESULTS AND DISCUSSION

On a broad scale, the results from the seismic tomography show the expected structure, with a high velocity body associated with the Mt Isa block sandwiched between the lower velocity Georgina, Eromanga and Carpenteria sedimentary basins. Within these broad structures, a range of smaller-scale features is evident. While increasing period generally corresponds to increasing depth, the relationship is not simple. It depends on the local vertical velocity structure and is complicated by irregular sampling of lateral variations. As a result, the conversion is neither simple nor necessarily unique, so the tomographic sections are presented for surface wave periods ranging from 2 to 10 s, which progressively sample deeper into the upper 10 km of the crust. The sensitivity kernels contained in the Figure A2 give an indication of the depth range sampled by each period.

Mt Isa block

Our results show a variety of features that are visible in the group velocity maps. In Figure 4, images at 2, 5 and 10 s are compared with the generalised tectonic map of the region and a Bouguer gravity anomaly map (Bacchin et al. 2008). In the shallowest image at 2 s, tomographic inversion accurately delineates the borders of the Western Fold Belt (WFB), Kalkadoon-Leichhardt Belt (KLB), and Eastern Fold Belt (EFB). In the middle zone, the KLB is marked by elevated group and phase velocities, with a clear north-south trend. In general the WFB has lower velocities compared with the other two belts of the Mt Isa domain. Two high-velocity regions in the EFB shown in the 2, 5, and 10 s group velocity images correspond to granites in the northeast and southwest. The
Figure 4: Comparison of group velocity images with tectonic features (a); Bouguer gravity (Bacchin et al. 2008) (b); and gridded temperature distribution at 5 km depth: OZTEMP (Gerner & Holgate 2010) (c). Circles denote the actual location of temperature measurements. Low seismic velocity regions that match gravity lows are marked with numerals. Dashed lines show the inferred boundaries of blocks and basin structures at depth, and dashed ellipses highlight known granite bodies.
isolated low-velocity patches at 2 s period marked with $D$
and at 5 s period marked with $E$ also correlate with features
in the gravity image indicating low-density regions. In general the extent and direction of the anomaly associated with the KLB appears consistently through increasing period up to 10 s; the surface waves at this longer period sense deeper material from upper
to midcrust and the influence of the surface material is reduced. The images suggest a slight westerly dip for the
KLB in depth.

To the north of the Mt Isa domain (north of 19°S), there are no features evident because of lack of path coverage traversing this region. Similarly, to the south (21.5°S and below), the resolution decreases drastically and smearing effects with elongated features begin to appear, for example in the 3 s images between latitudes
142°E and 139°E.

Sedimentary basins

The Georgina Basin to the west of the Mt Isa block is characterised by low group velocities with perturbations close to ~0.8 km/s from the mean in the shallow images from 2 to 5 s. The southerly extent of the Georgina Basin is not captured completely owing to the reduced path density but the northern end of the Georgina Basin shows up strongly over a range of depths. The extent of the low-velocity anomalies is in good agreement with the Bouguer Gravity map features marked with $A$ and $B$ in Figure 4. In Figure 3, the signature of Georgina Basin completely disappears for periods longer than 8 s.

The area west of Mt Isa represents a stratigraphic thickness much greater than other parts of the Georgina Basin. The AP Morstone 1 Well, north of the Camooweal to Burketown Road, penetrated 335 m of middle Cambrian limestone (Georgina Basin) overlying 427 m of sandstone, siltstone and claystone (of unknown correlation and age) (Withnall & Hutton 2013). The age or affinity of the sandstone/claystone sequence is uncertain but may be equivalent to the South Nicholson Group, which outcrops to the north (Withnall & Hutton 2013). If these rocks were equivalent to the South Nicholson Group, then they would clearly represent a significantly thicker sequence than occurs elsewhere. Alternatively the sedimentary rocks may be Neoproterozoic, and also form an anomalously thick sequence. The South Nicholson Group is up to 3.5 km thick (Sweet pers. comm. 2013), but depth to magnetic basement modelling in the area west of Mt Isa (Geological Survey of Queensland 2011) suggests that up to 6 km of sedimentary rock occurs in this structure. These depths are consistent with the low-velocity anomaly; visible to about 8 s (features marked with $A$ and $B$ in Figure 4–2 s). The significance of this interpretation is that the area represents an anomalously thick sedimentary rock accumulation, which is not present in other areas under the Georgina Basin. This thickness of sedimentary rocks was deposited in a geodynamic setting that does not occur elsewhere beneath the Georgina Basin.

The Carpentaria Basin is an offshore basin starting in the Gulf of Carpentaria and extending into north Queensland, with a thickness over 1.5 km (Korsch et al. 2012). In the group velocity images (2–4 s) for the shallow crust, the boundary between the Carpentaria and Eromanga basins can be inferred from a relatively straight feature (see dashed red line in 2 s group velocity image in Figure 4). In between these, localised low-velocity bodies appear. For example, to the south of 20°S, the signature of one such localised body marked with $F$ is visible both in the Bouguer Gravity anomaly and in all of the group velocity images.

MILLUNGERA BASIN

Following deep seismic reflection sounding in north Queensland conducted by Geoscience Australia in 2007, the presence of a new sedimentary basin underneath Carpentaria and Georgina Basin was revealed (Korsch et al. 2011, 2012) (see Figure 4a). Subsequent magneto-telluric surveys confirmed the existence of a significant conductivity contrast associated with the presence of the basin. The age of the Millungera Basin is uncertain. Preliminary Rb–Sr dating of illite from drill core indicates that the sediments were affected by intermediate (250–300°C) temperature tectonic and hydrothermal events about 1100 Ma (Uysal pers. comm. 2013). This suggests that the Millungera Basin is Mesoproterozoic and may correlate with the South Nicholson Basin (Jell 2013). It has been conjectured that this recently discovered basin has the potential to act a blanket above inferred highly radiogenic granites producing zones of anomalously high subsurface temperature. The outline of the Millungera Basin used in Figure 4a is deduced from seismic reflection imaging and magneto-telluric surveys conducted in the region. Our seismic tomography images using ambient seismic noise do not show a single consistent velocity anomaly in the vicinity of the Millungera Basin. Instead, a fragmented structure exists with a number of high and low-velocity bodies.

Seismic velocities are influenced by temperature as well as the mineral composition. Seismic ambient noise imaging across Australia by Saygin & Kennett (2010, 2012) revealed the influence of thick blanketing sediments and high heat generating regions. However, in seismic velocity tomography it is not in general possible to distinguish thermal and compositional effects contributing to velocity anomalies. In the seismic tomography images shown in Figure 3, the main patches of low-velocity anomalies can be interpreted as a result of the low-velocity thick sediment combination of the Carpentaria and Millungera basins in north and the Eromanga and Millungera basins in the south. The isolated low-velocity patches between 140.5 to 142°E and 18.5 to 20°S are examples of this pattern.

HIGH HEAT GENERATING ZONES

Figure 4c shows a compilation of temperature estimates at 5 km from the OZTEMP model of Gerner & Holgate (2010) derived from all available borehole temperature measurements across the Australian continent. Some of the noticeable low-velocity anomalies located east of 141° in the group velocity images are in good agreement
with the features of the OZTEMP model. However, the sampling in the OZTEMP dataset is not regular and did not extend across all the anomalies visible in tomographic images. Additional heat flow measurements have been undertaken from drill holes GSQ Julia Creek 1 (Faulkner et al. 2012) (feature H in Figure 4b) and GSQ Dobbyn 2 (Fitzell et al. 2012) (feature C in Figure 4b). Heat flows measured at 113.0 ± 2.9 mW/m² (GSQ Julia Creek 1) and 107.5 ± 1.7 mW/m² (GSQ Dobbyn 2) lie well above the regional average of 65–90 mW/m². These high heat flows are believed to result from high heat-producing granites underlying the Millungera Basin and Carpentaria Basin sedimentary rocks and correspond to low seismic velocity regions, which are interpreted as being caused by higher heat production than surrounding rocks. Some of the unmarked anomalies visible in Figure 4 such as 141'E, 18.5°–19°S, may well be associated with previously unrecognised high heat-generating regions.

CONCLUSIONS

The deployment of a set of portable seismic instruments in the Mt Isa region has allowed high-resolution seismic tomography by exploiting passive recording of ambient noise. Cross-correlations of records from pairs of stations allow the extraction of the surface wave portion of the seismic response of the structure between the stations, from which group velocities for the path can be found as a function of period (frequency). The full suite of path observations is employed in tomographic imaging to derive wavespeed maps as a function of period.

The complex geology of the region is reflected in the tomographic images, with distinctive geological features such as the Kalkadoon-Leichhardt, Western and Eastern Fold Belts readily recognised and tracked into depth through the proxy of increasing period. However, the recently discovered Millungera basin is not distinguished as a single feature in the images, perhaps as a result of multiple succession effects in the formation of the overlying basins.

Seismic wavespeeds can be affected by both compositional and structural affects, but in addition high temperatures can produce significant decreases in wavespeed. Isolated, but distinct, anomalies with lowered group velocity suggest the presence of local high heat production beneath the Millungera basin. However, there is also the possibility that these features might arise from zones with high permeability, which also can produce lowered velocities.

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APPENDIX A: GROUP VELOCITY ESTIMATION FROM GREEN’S FUNCTIONS

Group velocity

For two seismic stations A and B, the cross-correlation of simultaneously recorded ambient noise can be represented in the frequency domain as

\[ G_{AB}(\omega) = \int_{-\infty}^{\infty} \text{d}u U_A^*(\omega) U_B(\omega) \exp(-i\omega t) \]

where \( U \) is the recorded displacement at a station, \( G_{AB} \) is Green’s function between A and B, and \( \omega \) denotes the complex conjugate.

Surface waves are subject to dispersion when passing through Earth owing to the influence of the increasing seismic wavespeed with depth that is preferentially sampled by longer period waves. The dispersion has a modulating effect on the shape and speed of the waveform, which can be used to probe structure. For example, lower frequencies tend to penetrate deeper and...
therefore sample deeper structures. The group velocity, corresponding to the velocity of energy propagation, can be measured for a set of periods by applying a narrow-band Gaussian filter to a single Green's function (Figure A1). The maximum of the envelope shows the arrival of a packet and the velocity can be estimated using the distance between two stations and measured arrival time. In group velocity filtering, the measurement can be described as

\[ G_{AB}(\omega_c) = H(\omega_c) G_{AB}(\omega) \]

where \( H(\omega_c) \) is narrow-band Gaussian filter kernel and \( \omega_c \) is the chosen centre frequency for narrow band filtering. A detailed account of the processing steps is given in Saygin & Kennett (2010).

**APPENDIX B: RESOLUTION ISSUES**

**Depth sensitivity kernels**

The depth resolution attainable with seismic surface waves can be described by sensitivity kernels in depth, which require knowledge of the seismic velocity model. In Figure A2, two sensitivity kernel plots for Rayleigh wave group velocity are given for cratonic and sedimentary environments. Each peak of the normalised amplitude of the sensitivity curves indicates the dominant depths that surface wave will sample. Note the strong

**Figure A1** Group velocity measurement procedure for Green’s function of a station pair located in the Eromanga basin. (a) Time–group velocity relation. Hot colours indicate localised energy. (b) Same analysis for different frequency bands. The grey curve indicates the envelope of the corresponding Green’s function. The later arrival of wavelets with increasing frequencies indicates the dispersion effect.

**Figure A2** Rayleigh wave group velocity sensitivity kernels for two different models. The peak amplitude of each curve shows the dominant depth that the surface wave is sensing. (a) Fast crustal velocity model representative of the Mt Isa domain. (b) Same model with a 2.5 km thick low-velocity cover at top, characteristic of surrounding sedimentary basin areas.
influence of the shallow structure on the shape of the sensitivity kernels.

**Spatial resolution**

In Figure A3 we present representative tests of spatial resolution based on the recovery of a pattern of imposed wavespeed perturbations. We have used a two-dimensional sinusoidal form. We have not used the more conventional ‘chequerboard’ style of perturbation because this is not appropriate to the measurements that we are making. As can be seen from Figure A3, which shows results at both 3 s and 8 s periods, in the central portion of the area with the dense station spacing recovery of both the geometry and amplitude of the anomalies is good. But, away from this zone, the geometry of available paths leads to smearing and streaking and poor amplitude recovery.

**Figure A3** Synthetic tests for an input model of two partially superposed sinusoids. (a) Input model. (b) Recovered model for 3 s. (c) Recovered model for 8 s. The inset maps show the raypath distribution of travel times used in this study.