Application of Ground Penetrating Radar (GPR) to Detect Joints in Organic Soft Rock

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Abstract

The detection of joints and discontinuities is of particular importance to the stability of a broad range of geostructures including slopes, underground and open-pit mines. As a common example, the mechanical response of soft rocks observed within open-pit mines is significantly influenced by the existence of joint networks, resulting in a complex stress distribution which governs the stability factor of safety as well as the failure mechanism. In this paper, surface geophysics scanning by ground penetrating radar is presented for the detection of vertical joints at one of the largest open-pit coal mines in Australia. The optimum soil velocity, point interval and antenna frequency for joint detection in Victorian Brown Coal (VBC) are presented in comparison with electromagnetic properties of known organic soils. Furthermore, the performance of an assorted set of post-processing signal filtering techniques to successfully identify the underground coal fractures are detailed, along with obstructions affecting the feasibility of GPR vertical joint discovery in this light organic soft rock.

Keywords:

Joint detection

Ground penetrating radar

Intermediate geotechnical material

Victorian brown coal

Introduction

The Latrobe Valley brown coal fields excavated using present day open-cut mining technology represents about 25 % of Australia's total fossil energy reserves and is one of Australia's major national sources of energy supply (Guy and Perry, 1992). They are situated around 150 km east of Melbourne in the State of Victoria. Traralgon, Morwell and Yallourn formations contain the three main brown coal seam groups which form some of the thickest continuous coal successions in the world (Barton et al., 1993). As the second largest open-cut mine in Australia, Yallourn mine is one of the three open-cut brown coal mines in Latrobe Valley and fuels Yallourn Power Station with the capacity of 1480 megawatts. Yallourn Power Station supplies 22 % of state's and 8 % of Australia's electricity needs.

Since the start of coal mining at Yallourn open-cut in 1924, a considerable amount of expertise has been employed by geotechnical engineers and hydrogeologists to ensure the stability of mining batters. For about 100 years, engineers have worked on several factors that affect the stability of the batters, such as mining slope, geotechnical properties of Victorian Brown Coal (VBC), hydrogeology of the coal and interseam layers, and orientation of joints and discontinuities. However, in late 2007, an 80 m high batter collapsed and slid about 250 m across the Yallourn open-cut floor, taking with it 6,000,000 m^3 of coal and clay, and a mine road. Through post-failure investigations and reviewing the historical data in 2008, it was presumed that the rise in water pressures in a joint along the rear of the failure has increased the horizontal stress as the acting stress and shifted the batter in block sliding mode.

Since then, joint mapping and monitoring at Victorian brown coal mines have been performed more rigorously, and extensive dynamic digital database systems have been developed during the last ten years to monitor the behaviour of joints and displacement of the batters by the aid of Global Positioning System (GPS) and regular site inspections.

Although regular site inspection and spatial analysis of GPS and pin data are widely applied nowadays as effective joint management practices, the application of geophysical methods in detecting subsurface discontinuities is growing rapidly in this area. Electrical resistivity methods are used for mapping fractured rocks filled with some representative minerals (Orellana, 1972). Vertical anisotropy profiles of apparent electrical resistivity can be considered as a valuable tool for monitoring crack patterns at depth (Daniels, 1996). In some rocks, variation in the velocity of seismic waves can be used for mapping rock discontinuities. Ground Penetrating Radar (GPR) based on electromagnetic radiation is also used for detecting subsurface objects, cavities and geological discontinuities (Butnor et al., 2012, Zajc et al., 2014, Di Prinzio et al., 2010, Sagnard and Tebchrany, 2015, Barr, 1993, Conyers, 1995).

The Victorian Brown Coal (VBC) is a very light, organic and brittle non-textbook geotechnical material with the saturated unit weight of 12.5 kN/m^3. Due to the very high energy release rate of VBC, and decades of mining and stress relaxation in Yallourn open-cut, existing joints have propagated well across the thickness of coal seam. This fact eases the joint mapping practice in the areas where coal surface is uncovered. However, this practice can be extremely challenging where the coal surface is laid under a layer of sandy/gravelly overburden material, or the coal surface is face trimmed by dozers as a routine mining method in the Yallourn mine (Fig. 1).

In this paper, researchers at Geotechnical and Hydrogeological Engineering Research Group (GHERG), Federation University Australia, investigated the application of GPR with different wave frequencies, in detecting vertical subsurface joints in VBC covered by silt and gravel.

Fig. 1. Map of Australia showing the location of the Yallourn mine

Background

In general, GPR utilises electromagnetic waves to provide useful resolution and nondestructive measurements of dielectric contrasts in geological materials and formations (Daniels, 2004). Similar to most of the geophysical methods, this method can be classified as a nondestructive geophysical method by which electromagnetic waves are sent into the ground with an ability to gather data from underground soil without drilling and mechanical sampling. These electromagnetic waves are reflected back when they reach an underground object or a boundary between two different materials. In the end, GPR system detects the reflected wave and calculates the location of targets based on its time-distance algorithm (Hassan and Toll, 2014).

The history of using GPR dates back to 1904 when this method was used to detect remote terrestrial metal objects (Greve et al., 2010). After that, application of GPR continued for estimating the thickness of ice, fresh water, salt deposition, pavement, rock and coal (Greve et al., 2010, Hassan and Toll, 2014, Al-Qadi and Lahouar, 2005). In 1989 the Norwegian Geotechnical Institute (NGI) used georadar systems for applications in environmental purposes which have been tested in over sixty projects and found to yield satisfactory results (Cheng et al., 2013). The GPR scanning technique was also used to investigate backfilling of a retaining wall to find the location of bedrock when it was not possible to conduct traditional geotechnical field investigations (Beben et al., 2013).

GPR is also applicable in finding discontinuities in rocks. The reflection of electromagnetic waves happens at the interface between two media having different propagation velocities like the interface of a crack and the surrounding rock (Daniels, 2004). This concept has been successfully examined for detecting fractures and structural features in different rocks such as marble, granite and gneiss (Toshioka et al., 1995, Porsani et al., 2006, Kong and By, 1995, Cheng et al., 2013, Arosio, 2016). This method has been also used by (Orlando, 2003) to evaluate rock quality based on the concept that in good quality rock, most of the energy is transmitted, while in low quality rock, the energy is backscattered from fractures. The GPR scanning method has also been applied in airport road maintenance by identifying the location of subsurface cracks. This method has allowed the engineers to propose a repair program for the worse affected areas rather than a full-scale reconstruction, resulting in a significant saving in road maintenance cost (Grandjean and Gourry, 1996). The effectiveness of the GPR method has been examined by (Di Prinzio et al., 2010) to detect the presence of voids and discontinuities within levees and river embankments.

In mining engineering, in addition to batter stability investigations, mapping of fractures and unloaded joints by nondestructive geophysical methods such as GPR scanning helps the development of the quarry in a rational and profitable manner. This information is fundamental for guiding the development of new benches by avoiding areas with close-spaced fractures, thus optimising the extraction process and increasing benefits (Daniels, 2004). Also, GPR has been found as a successful crack detecting tool for monitoring of historical buildings (Stevens et al., 1995). In general, GPR scanning has been found as an effective method in capturing discontinuities and external objects within materials with low attenuation such as ice, sand, crude oil, rock and fresh water, and less effective in high attenuation media such as clay and salt water (Cheng et al., 2013).

Through the review of literature, it has been noted that although a number of studies have been conducted for the purposes of using GPR to detect discontinuities in different quarries, there is still a lack of research in the application of GPRs in finding cracks and joints in open-cut coal mines. Due to the low unit weight of VBC, pre-existing joints in VBC mines have a tendency to open and extend due to earthworks or excessive pore water pressure, explaining that joints in VBC mines can be considered as ongoing threats to the stability of batters. Hence, GPR scanning might be regarded as a useful field investigation method in VBC open-cut mining as well as a key component towards successful mine rehabilitation after closure, if it can be used for mapping of subsurface joints in a practical way.

Testing Program

The GPR system used in this research project consists of a control unit, an antenna (transmitter and receiver) and survey wheels (see Fig. 2). The control unit triggers the antenna to send radar waves into the ground and also receive the reflected waves. As a standard practice, survey wheels equipped with an odometer have been used to facilitate fieldwork and record reference points during surveying (Greve et al., 2010, Hassan and Toll, 2014).

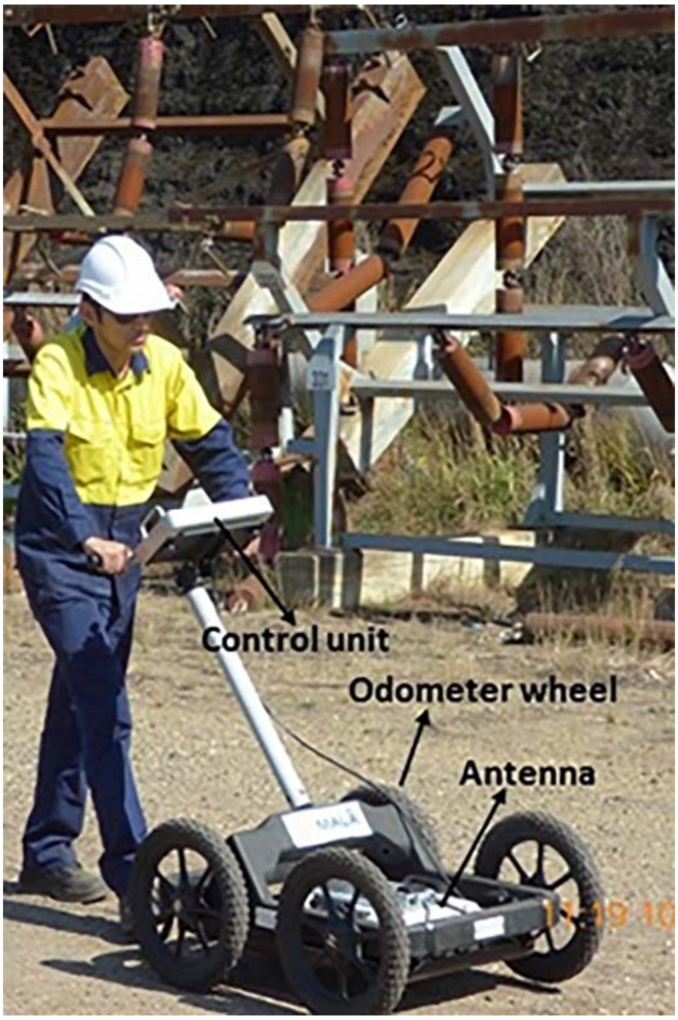


Fig. 2. Overview of the employed GPR system

Velocity of propagated GPR waves (radio signals) through subsurface is related to the electrical property of the underground materials and material's dielectric permittivity. When the radio signals reach the interface of two materials with different dielectric properties, a portion of the signal is returned back to the antenna on the ground surface. The control unit on the GPR system measures the amount of time taken for the radio signal to traverse to and from the target (two-way travel time) which indicating its depth and location of the target (Eq. 1) (ASTM, 2010).

$$D = \frac{t\,V}{2} \qquad (1)$$

where, V is the velocity of the electromagnetic wave in a material, D is the one-way distance to the object, and t is two-way travel time to the object.

In the ground, the velocity of electromagnetic waves (V) changes depending on the relative dielectric permittivity (Eqs. 2 and 3) (ASTM, 2010). The higher the dielectric constant, the lower the electromagnetic waves passing through the materials (Hassan and Toll, 2014, Kadioglu, 2008). Table 1 gives the electromagnetic characteristics of different materials.

$$V = \frac{C}{\sqrt{K}} \qquad (2)$$

$$K = \frac{\varepsilon}{\varepsilon_0} \qquad (3)$$

where, C is the velocity of light (0.2997 m ns^{-1}), K is dielectric constant, $\mathcal{E}$ is permittivity of the target and $\mathcal{E}_0$ is permittivity of free space (8.854×10^{-12} Fm^{-1}).

Table 1 - Approximate electromagnetic properties of some materials (ASTM, 2010)

Material	Dielectric constant (K)	Pulse Velocities (m/ns)
Air	1	0.3
Fresh water ^{f,t}	81	0.033
Sea water ^{f,t,s}	70	0.033
Sand (dry) ^{d}	4-6	0.15-0.12
Sand (saturated) ^{d,w,f}	25	0.055
Silt (saturated) ^{d,w,f}	10	0.095
Clay (saturated) ^{d,w,f}	8-12	0.106-0.087
Dry sandy coastal land ^{d}	10	0.095
Fresh water ice ^{f,t}	4	0.15
Permafrost ^{f,t,p}	4-8	0.15-0.106
Granite (dry)	5	0.134
Limestone (dry)	7-9	0.113-0.1
Dolomite	6-8	0.122-0.106
Quartz	4	0.15
Coal $^{d,w,f,\text{ ash content}}$	4-5	0.15-0.134
Concrete $^{w,f,\text{ age}}$	5-10	0.134-0.095
Asphalt	3-5	0.173-0.134
Sea ice ^{s,f,t}	4-12	0.15-0.087
PVC, epoxy, polyesters vinyls, rubber ^{f,t}	3	0.173

Note:
d: function of density,
w: function of porosity and water content,
f: function of frequency,
t: function of temperature,
s: function of salinity, and
p: function of pressure.

Choosing the right antenna is the key part of GPR testing programme. In general, the frequency of antennas available in the market varies from 10 MHz to 1.6 GHz. The frequency of GPR antenna is chosen according to the aims of the survey. In general, the deeper the penetration, the lower the antenna frequency and the lesser the resolution, and vice versa.

Table 2- Examples of scanning capability with different frequencies
(Hassan and Toll, 2014) and (ASTM, 2010)

Frequency	Typical application	Maximum depth (m)
1.6 GHz	Structural concrete, roadways, bridge decks	0.5
900 MHz	Concrete, shallow soils, archaeology	1
400 MHz	Shallow geology, utility, environmental, archaeology	3
200 MHZ	Geology, environmental	8
100 MHz	Geology, environmental	20

As explained before, there is a direct relation between antenna's frequency and resolution, and an inverse relation between antenna's frequency and penetration depth. Hence, due to the fact that joints in VBC formations commence from shallow depths (from the coal surface just underneath the overburden material) and are relatively closed, medium range frequency was considered to be suitable for this investigation. The equipment used in this survey is MALÅ Ground Explorer HDR, manufactured by Malå GeoScience Förvaltnings AB (GuidelineGeo, 2016), which consists of two antennae, one 450 MHz and the other one 750 MHz. According to Table 1, the velocity of electromagnetic waves in coal ranges between 0.134 - 0.15 m/ns. Thus, the velocities of 0.1, 0.13 and 0.15 m/ns are set on the control unit which runs a basic real-time processing during the test. This allows the user to find the possible location of the joints while the test is being conducted. The same range of velocities are used later during the data post-processing by a third party processing software package.

Two joints cutting through VBC formation at the northern batter of Yallourn mine (Fig. 3) are visible from the side and invisible at the ground surface are considered as benchmark joints for GPR scanning (Fig. 4 - 5). On the batter and access road both joints are covered with silty overburden material (0.5 m to 1 m thick) and compacted gravel and silt (0.2 m to 0.4 m thick), respectively, while they are exposed at the batter face. Since the location of covered joints under the overburden layer and access road pavement are seen from the side view, this spot provides a good location for investigating the capabilities of GPR in this joint mapping exercise. As shown in Fig. 5, two tracks perpendicular to the joints are defined as survey lines, one 21 m long on the batter (Survey Line 1) and the other one 56 m long on the access road (Survey Line 2).

A total of twenty scan runs were conducted. Eight along the Survey Line 1, and twelve along the Survey Line 2 (Fig. 6), with a range of varying parameters as shown in Table 3. These parameters were altered on a “one factor at a time” basis to determine the best framework for joint detection.

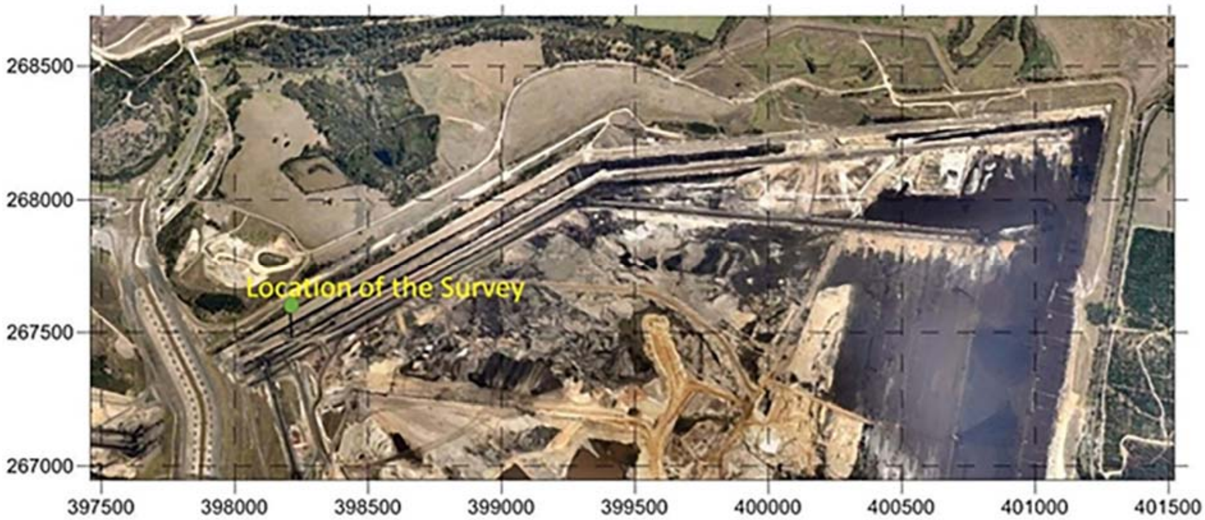


Fig. 3. Location of survey

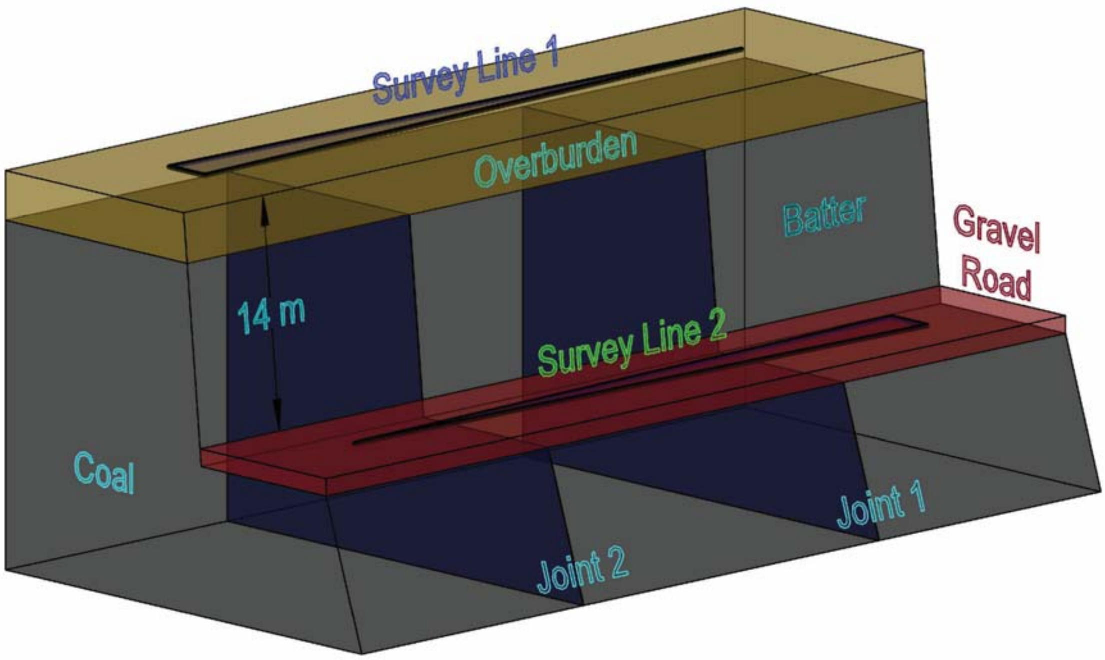


Fig. 4. Schematic diagram of the survey lines

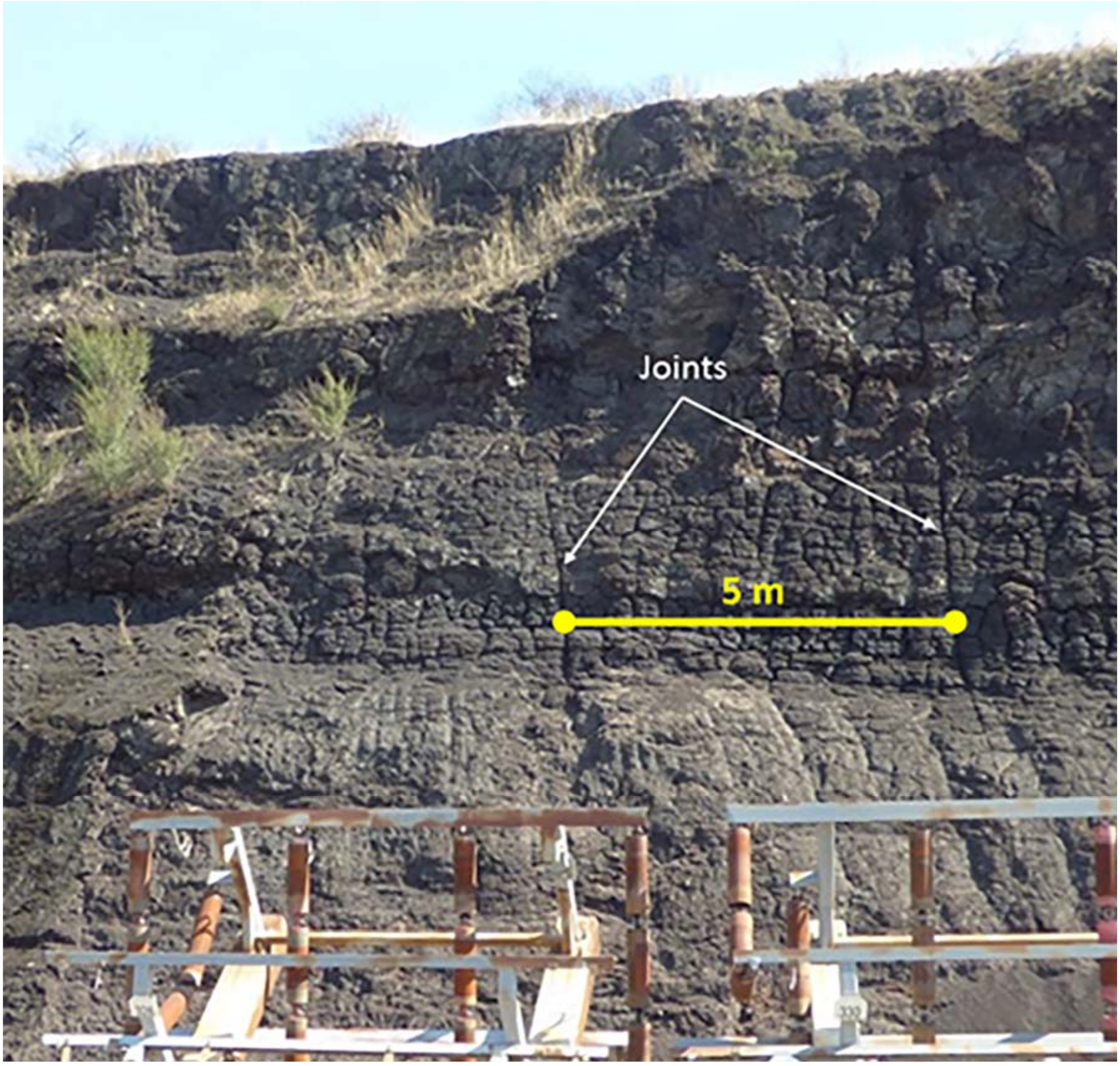


Fig. 5. Side view of the joints at the VBC batter

Fig. 6. Scanning on Survey Line 2

Table 3 - Test parameters

Test number	Location	Antenna frequency (MHz)	Soil velocity (m/ns)	Point interval (cm)
1	Survey line 1	450	0.130	1
2	Survey line 1	450	0.130	1
3	Survey line 1	450	0.130	1
4	Survey line 1	450	0.100	1
5	Survey line 1	450	0.100	1
6	Survey line 1	450	0.150	1
7	Survey line 1	450	0.150	1
8	Survey line 1	450	0.150	1
9	Survey line 2	750	0.130	1
10	Survey line 2	750	0.130	0.5
11	Survey line 2	750	0.100	0.5
12	Survey line 2	750	0.150	0.5
13	Survey line 2	750	0.100	1
14	Survey line 2	750	0.150	1
15	Survey line 2	450	0.130	1
16	Survey line 2	450	0.100	1

17	Survey line 2	450	0.150	1
18	Survey line 2	450	0.130	0.5
19	Survey line 2	450	0.100	0.5
20	Survey line 2	450	0.150	0.5

Data processing

Once testing was completed, the data was uploaded from the GPR unit memory and analysed with the R computer software package RGPR (Huber and Guillaume, 2017). GPR images viewed in their initial unfiltered state proved ineffective in identifying the positions of joints (Fig. 7). Furthermore, virtually no discernible details were able to be identified, suggesting the suitability of filtering techniques to enhance image quality.

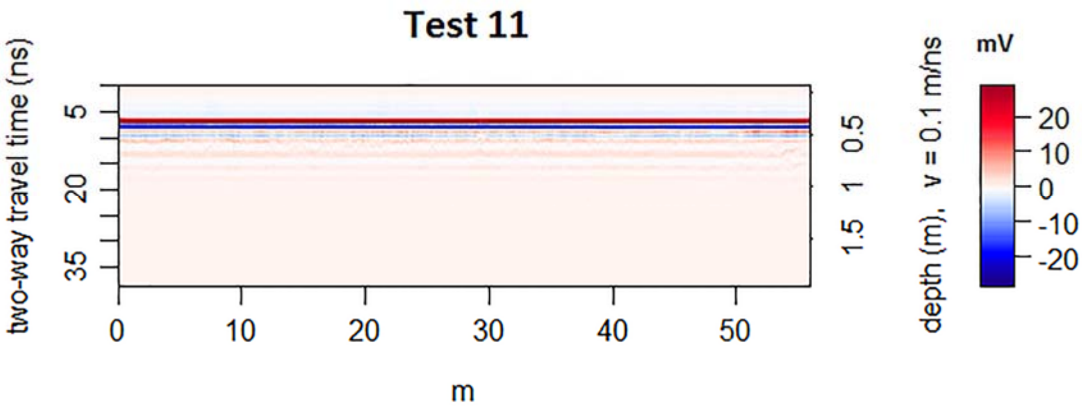


Fig. 7. GPR image of Test 11 before post processing

To produce images of high detail, a procedure utilising a range of filtering techniques (Fig. 8) was devised with the objective of improved visualisation of joint features:

DC shift removal

Due to the energy input from the air and ground waves, the GPR receiver signal becomes saturated, introducing low frequency components known as “wow”. A bulk DC shift in amplitude towards zero is applied as a correction.

Bandpass filtering

A bandpass filter is an algorithm that permits frequencies of a given range while rejecting all frequencies outside the range. In this case, higher frequencies were filtered out, effectively removing signal noise, allowing key joint characteristics to be identified without the interference of small and desiccation cracks. Davis and Annan (1989) stated that “GPR systems are designed to achieve bandwidths that are about equal to the center frequency”. Hence the bandpass filter ranges implemented were 225 - 675 MHz and 375 – 1125 MHz for the 450 and 750 MHz antennae, respectively.

Gain recovery

Time gain recovery was applied to account for the effects of signal attenuation. The exponential gain function applied is given in Equation 4

$$A_{gain}(t) = A(t)\exp(\alpha\, t) \quad (4)$$

Where A(t) is the initial signal, α is the exponential gain constant, and t the sample trace (ns). The exponential gain constant α of 0.5 was determined to give the best visualisations for the test instances considered in this paper (Cassidy, 2009).

Inverse normal transformation

A histogram of frequencies (Fig. 9) indicates a narrow band of values about zero. To broaden the spectrum, a rank based inverse normal transform is implemented, producing a wider spectrum (Fig. 10).

Median trace filter

A median trace filter (or alpha-mean trim) is applied to vertically along each trace, removing high frequency noise spikes (Cassidy, 2009).

Contrast control

The image colour contrast is maximised to highlight potential joint locations.

When analysing the Global Positioning System (GPS) coordinates taken along Survey Lines 1 and 2, it was noted that the two lines were not completely parallel. To remedy this, a scalar projection of Survey line 1 coordinates was projected onto Survey line 2 suggesting that Joints 1 and 2 should be located at 29 and 36 m along Survey Line 2, respectively.

A time-zero correction is commonly used in GPR studies to designate the starting point of the received wave form. A correction is often applied to rescale depths, such that the ground surface occurs at 0 m. Due to the vertical nature of the joints of interest in this study, it was deemed unnecessary to perform a time-zero correction, as the detection of the below the surface joint locations was the prime objective. As the rescaling of vertical depths by less than 0.5m provides no further information for the purposes of this study, no zero-time correction was performed.

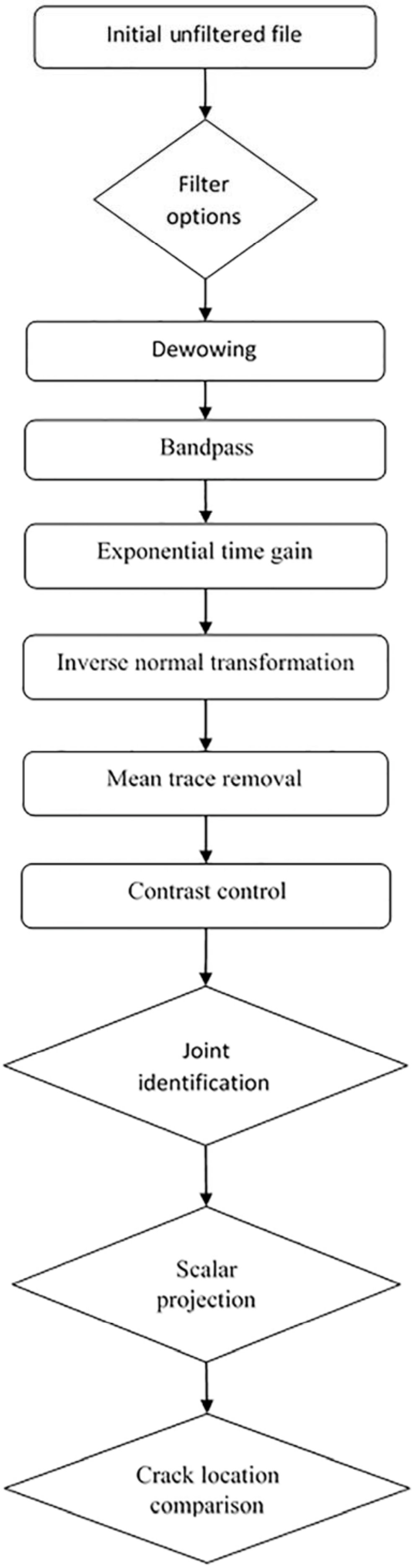

Initial unfiltered file
Filter options
Dewowing
Bandpass
Exponential time gain
Inverse normal transformation
Mean trace removal
Contrast control
Joint identification
Scalar projection
Crack location comparison

Fig. 8. Flowchart of data post-processing and joint identification

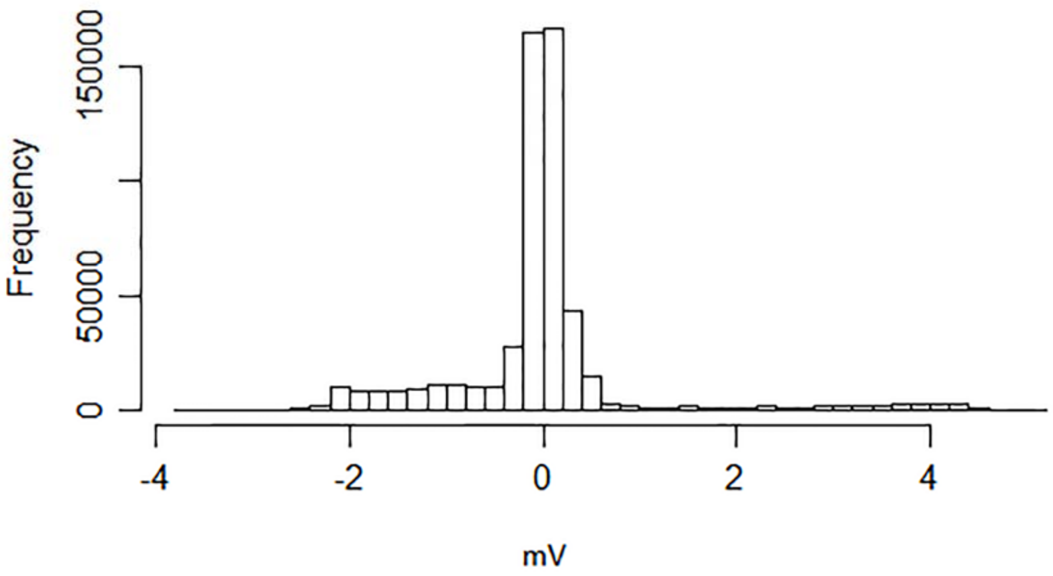


Fig. 9. Histogram of frequencies, indicating a narrow peak, Test 9

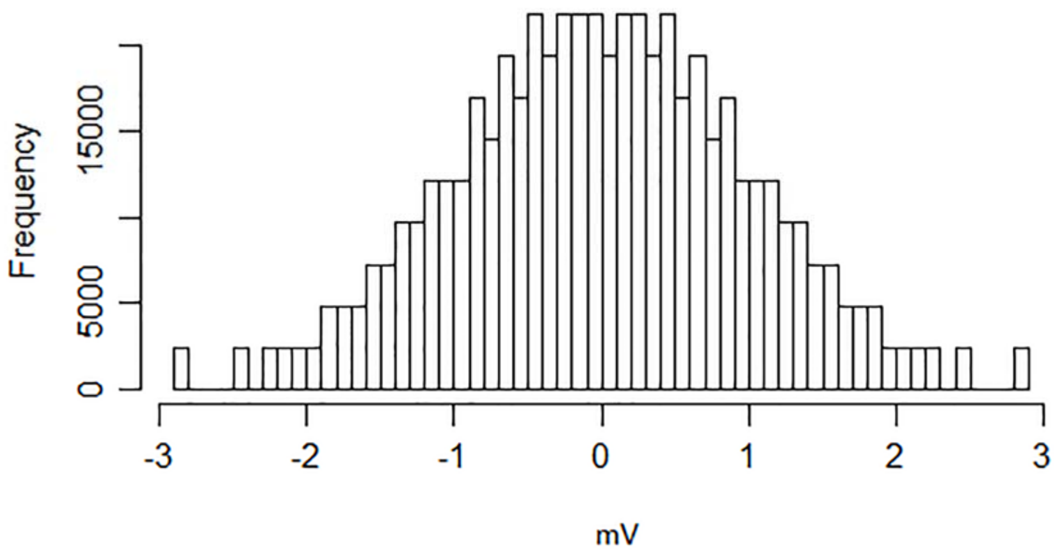


Fig. 10. Histogram of frequencies, indicating a broadened peak after Inverse Normal Transformation, Test 9

Results and Discussion

Tests with a point interval parameter value of 0.5 cm (Tests 10 - 12, 18 - 20) proved too grainy for further analysis (Fig. 11). For this reason, only point intervals of 1 cm were considered for additional investigation.

The impact of the variation of soil velocity and antenna frequencies on joint visualisation is clearly visible in Fig. 12 for the 750 MHz antenna, conducted along the base of the batter, with vertical joints discernible at 29 and 36 m. Joints 1 and 2 are located at 31 and 38 m in Test 14, due to a difference in the test starting position. The two joints are best visible in Test 12, with a soil velocity of 0.15 m/ns, whereas the lower soil velocities of 0.1 and 0.13 m/ns were unable to easily locate both joints together (Tests 9 and 13). In both tests, Joint 1 was easily located, however Joint 2 appears only as a small anomaly. Tests 15, 16 and 17 were performed with a 450 MHz antenna (Fig. 13). Although Joints 1 and 2 are visible in Tests 16 and 17, the quality of the joint visualisation was considerably lower than with the 750 MHZ antenna, suggesting that 450 MHz is an unsuitable frequency for detection of coal joints of this type. Fig. 13 indicates that there are potentially numerous desiccation cracks running through the VBC batter. However, two prominent joints are visible at 29 m and 36 m, being the two joints detailed in Fig. 5 In addition to the observed joints, a number of surface cracks are visible in Fig. 13 that do not appear to propagate vertically through large depths of the coal.

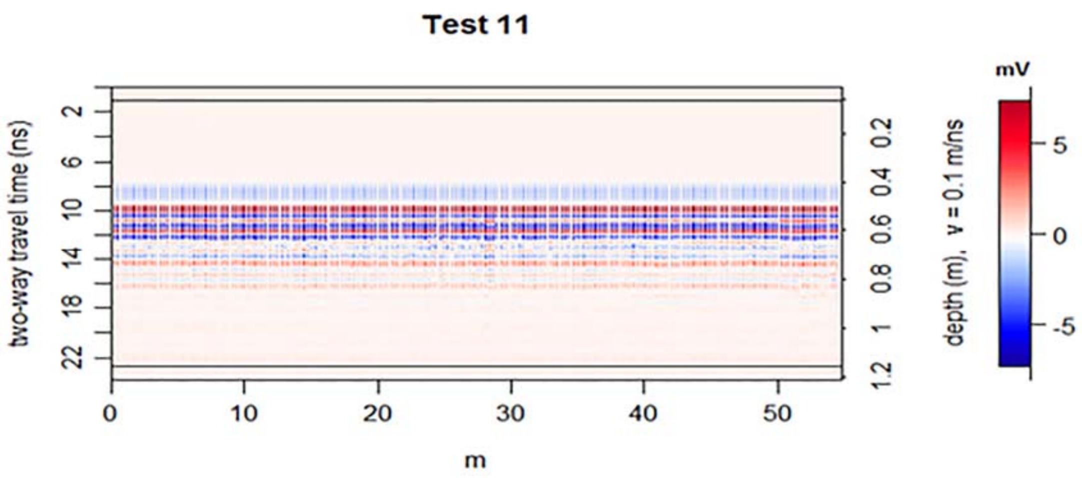


Fig. 11. Test 11 results, Point interval: 0.5cm

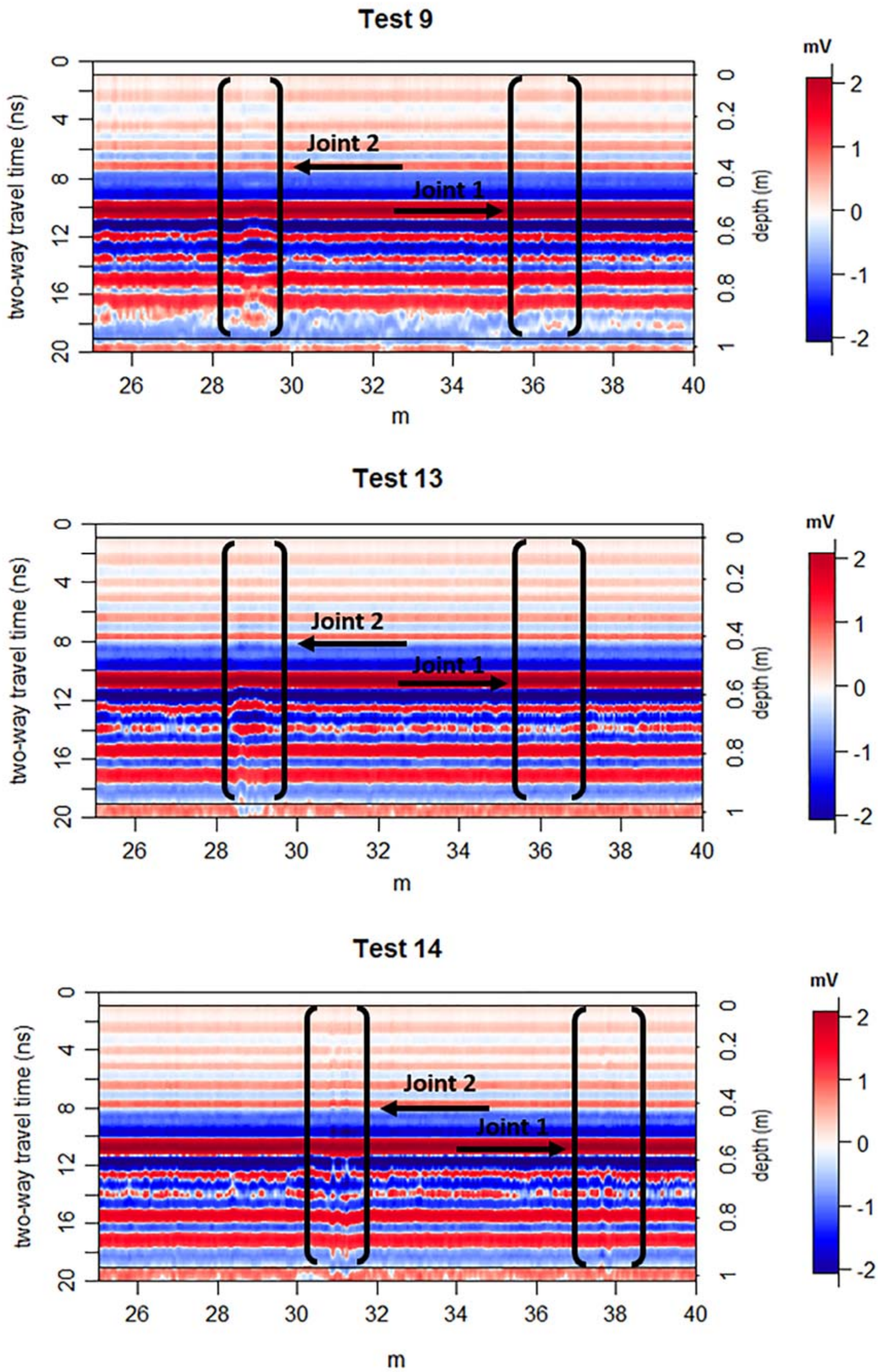
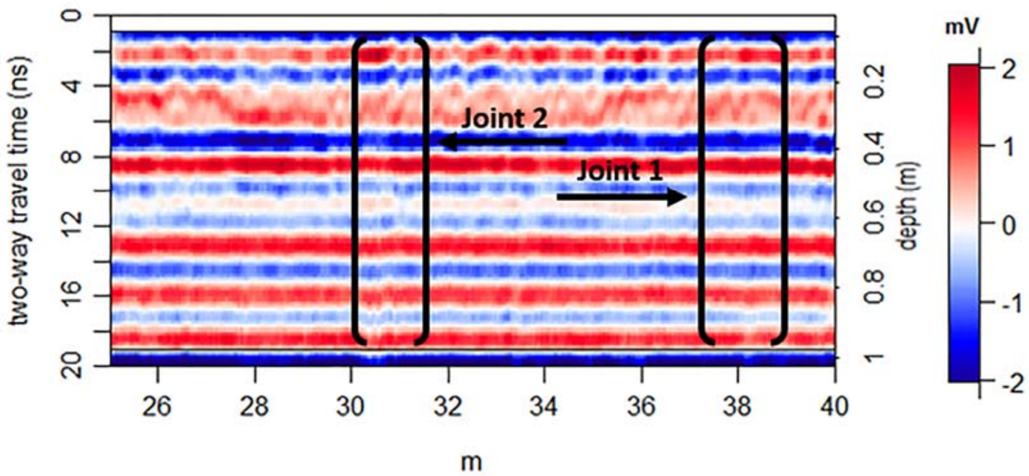
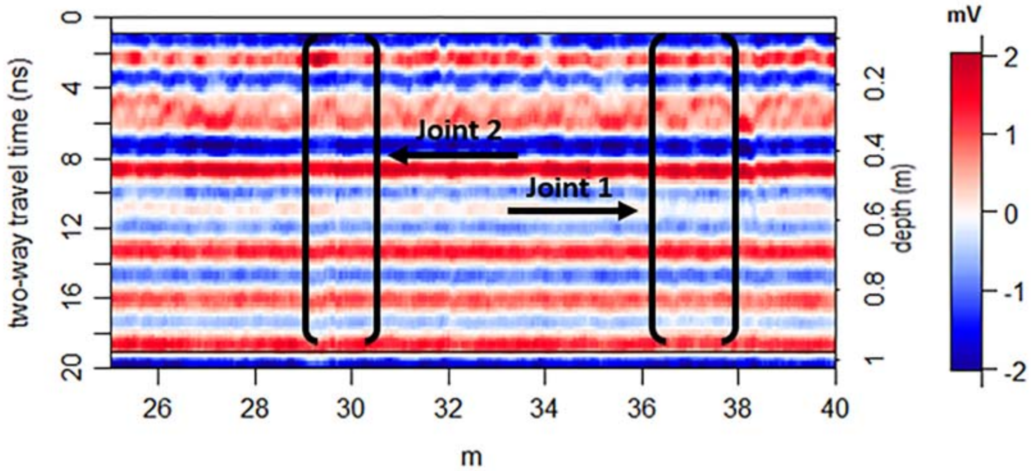


Fig. 12. Varying joint resolution for the 750 MHz antenna (Survey Line 2)

Test 15



Test 16



Test 17

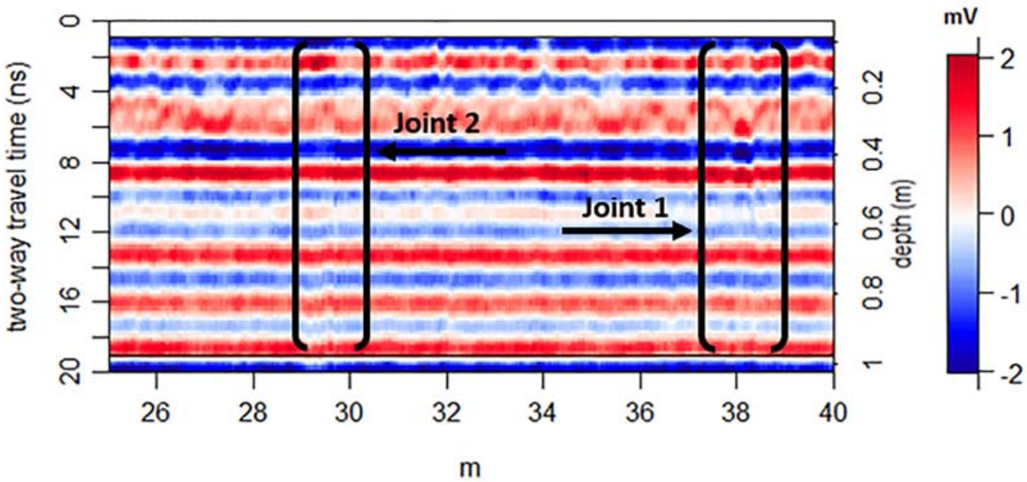


Fig. 13. Varying joint resolution for the 450 MHz antenna (Survey Line 2)

The location of Joints 1 and 2 are visible along Survey Line 1 at 15 and 10 m respectively (Fig. 14). It is noted that the two main joints identified along Survey Line 1 align with those of Survey line 2, within acceptable experimental error due to variation in the initial start position along the survey lines. The joints along Survey Line 1 are best visualised in Test 7 and 8 (Fig. 14) with a soil velocity of 0.15 m/ns. It is notable that the batter contains numerous fractures, with two further large joints visible at 5 m and 18 m. Although joints along Survey Line 2 were best observed with an antenna frequency of 750 MHz, the main joints along Survey Line 1 are not easily distinguished at this frequency, due to the numerous other fractures. Hence, heavily jointed coal was considered with the 450 MHz antenna.

In both cases, the highest soil velocity (0.15 m/ns) provided the best joint resolution, however the considerable number of joints along the batter provides a considerably challenging environment for locating specific joints. Nevertheless, the most apparent of the joints can be differentiated from smaller fractures. It is suggested that the joints were difficult to locate due to their vertical nature, and could have been identified if their angle with the ground surface was smaller.

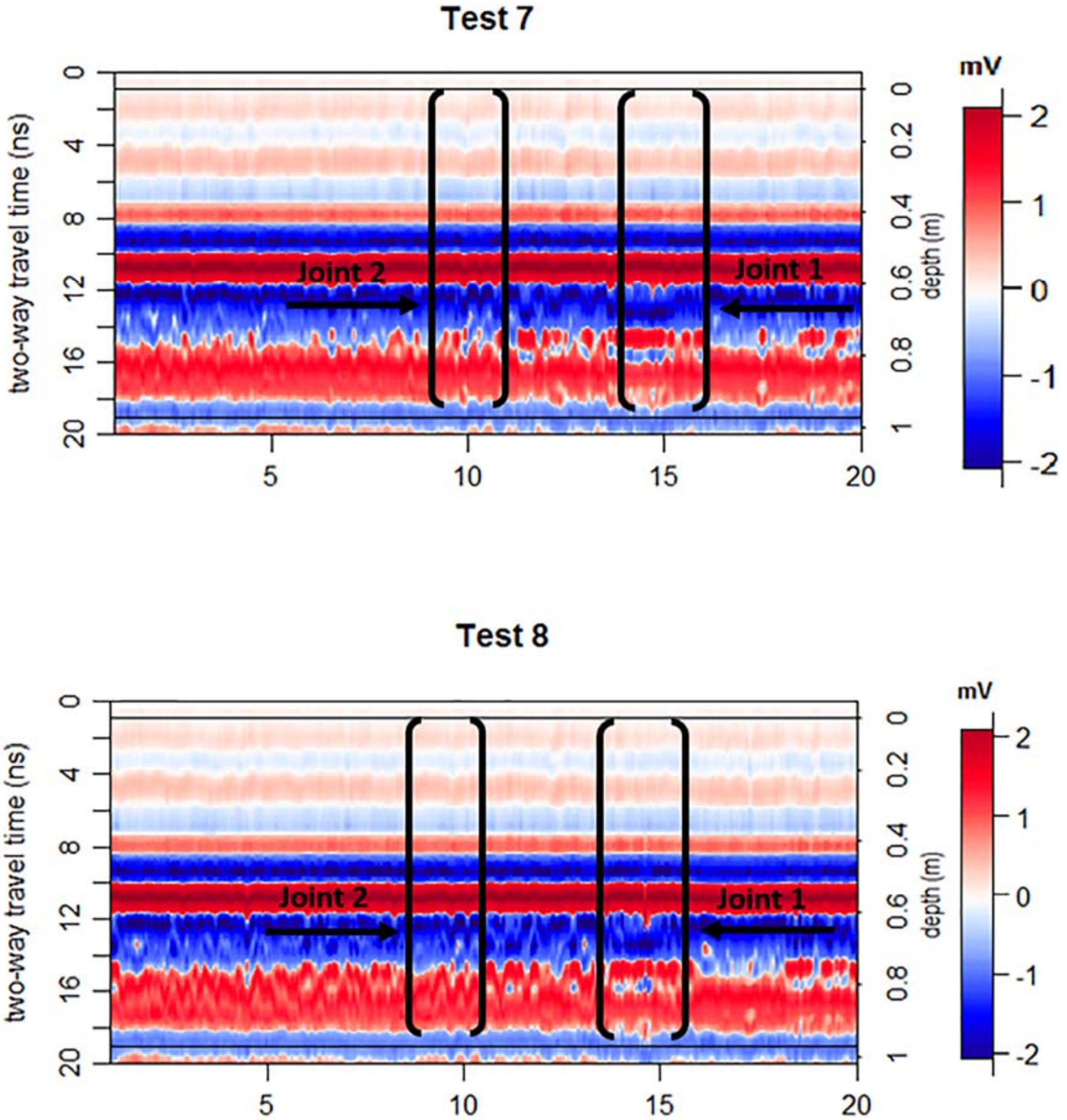


Fig. 14. Varying joint resolution for the 450 MHz antenna (Survey Line 1)

Conclusion

Ground Penetrating Radar (GPR) can be considered as a useful tool for a broad range of geotechnical investigation purposes. In this study, GPR was adopted as a technique for the identification of pre-existing vertical joints in Victorian brown coal, due to the method's non-destructive qualities. Two survey tracks were constructed to identify known batter joints, visible to the naked eye from the side view and fully covered at the ground surface.

With the variation of a range of parameters including soil velocity, point interval distance and antenna frequency, these known joints were detected. Although this method was theoretically feasible, joint detection requires numerous parameter variations and significant post-processing using software tools. Furthermore, the joints identified were visible within the coal batter. Hence the process of verifying their locations on GPR images was straightforward. It is suggested that determining the locations of unexposed joints may prove exceedingly more complicated, especially when considering surveying on the magnitude of large sections of mine slopes.

To determine joints within Victorian Brown Coal, a 1 cm point interval resolution, with a 450 MHz antenna for heavily jointed environments and 750 MHz for infrequently jointed conditions is recommended. The joints were best observed at a soil velocity of 0.15 m/ns.

To view these fractures, considerable data processing was required, with a number of filters implemented, including DC shift, bandpass, median trace and gain filters.

For the reasons detailed above, it is suggested that GPR detection of brown coal joints is a theoretically valid method. However, the technique is impractical in reality due to poor resolution and the need for excessive filtering of results.

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