Three Dimensional, Multi-Offset GPR Imaging of Archaeological Targets: Groundwell Ridge, Swindon

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Abstract

The application of ground penetrating radar (GPR) methods to the imaging of archaeological targets has been widely documented over the last 20 years. In spite of many successful applications, the use of the GPR technique is still impeded when low signal-to-noise ratio (SNR) data are obtained. Such data quality may result when a) surveying over an electrically conductive subsurface, b) where a target has a low physical contrast with host media, or c) where subsurface reflectivity is structurally complex. Three-dimensional (3-D), multi-offset (MO) GPR surveying offers the potential to improve the GPR image of a target where such problems exist. The 3-D survey facilitates the process of 3-D migration, allowing complex structure to be correctly imaged. The MO method is a means of boosting signal amplitude, thereby improving signal-to-noise ratio (SNR) in low-signal data. The application of these techniques to the GPR setting is rare, but rarer still are documented examples of their integrated use. We therefore acquire archaeological GPR data using 3-D and MO surveying techniques to investigate the improvement to image quality when compared to a more conventional acquisition and processing strategy. GPR data were acquired in Spring 2006 over a known Romano-British target at Groundwell Ridge, near Swindon, UK, using a Sensors & Software pulseEKKO1000 system equipped with 450 MHz antennae. 3-D methods were facilitated by acquiring data with a sample density of 5×5 cm^2. The MO acquisition was sampled with equal density over an area of the archaeological target where SNR was notably low and the interpretation of structure in archive datasets was cautious at best. The MO data were acquired to provide an expected factorial increase in SNR of 4·5 on processing. Use of 3-D methods significantly improves the spatial resolution of the output archaeological image; exterior walls are clearly imaged, together with the layout of interior rooms. The MO acquisition improves SNR such that the cautiously interpreted structure is more clearly imaged hence the interpretation can be made with more certainty. Further work is currently needed to quantify any image enhancement and to find a compromise between such detailed sampling and output image quality.

1. Introduction

The archaeological subsurface represents a potentially difficult problem for imaging targets with ground penetrating radar (GPR) systems. Structures within the ground may be very steeply dipping or exhibit large local variations in strike causing serious migration problems. Furthermore, the target may be located in a medium that is electrically conductive (e.g., clay-rich or waterlogged soil) such that the GPR wavelet is rapidly attenuated and the signal-to-noise ratio (SNR) in the resulting dataset is diminished. Recently, techniques used routinely by the seismic industry for imaging complex, low-SNR targets have been imported to the field of GPR acquisition. Specifically, use of three-dimensional (3-D) migration has been shown to significantly improve the resolution of the GPR target in regions of structural complexity (Grasmueck *et al.*, 2005), whilst the multi-offset (MO) method has been employed to boost SNR over otherwise poorly defined targets (Yilmaz, 2001). When these methods are combined, the potential improvement to the image of an archaeological target may be considerable. An integrated 3-D, MO GPR acquisition was performed over an archaeological target, over a Romano-British villa at Groundwell Ridge (Linford and Linford, 2004) in Spring 2006. A grid of dimension 21 × 14 m^2 was sampled extensively using a Sensors & Software *pulseEKKO1000* GPR system equipped with 450 MHz antennae, and afterwards with topographic levelling equipment. On processing, the image of the archaeological target is indeed significantly improved by use of the 3-D and MO methods. Such high quality images may only be obtained, however, if a GPR surveyor satisfies rigorous acquisition criteria that require significant increases in acquisition and processing effort.

2. Theoretical Background: The Multi-Offset Method

GPR data are conventionally acquired with a *common offset* (CO) antenna configuration. This involves keeping the separation between transmitting (Tx) and receiving (Rx) antennae fixed at all sample locations, shown schematically in Figure 1a. The fixed antenna separation implies that subsurface reflection points will be imaged once only. Where data are acquired with a *multi offset* (MO) antenna configuration, the separation between antennae is incrementally increased about some fixed surface location; the resulting dataset is termed a *common midpoint* (CMP) *gather* (shown schematically in Figure 1b). Notice that the reflection points beneath the midpoint are imaged multiple times; this repeated imaging leads to a means to boost signal-to-noise ratio (SNR). MO data are acquired most efficiently if, rather than using CMP gathers, data are acquired using *common source* (CS) *gathers*. Shown schematically in Figure 1c, the CS gather involves fixing the location of Tx and gradually increasing the offset to Rx. Once the desired maximum offset is reached, Tx is moved to the next source position and a further CS gather is acquired. On processing, the repeated imaging of subsurface reflection points leads to an increase in SNR; MO methods are therefore particularly useful for boosting signal level in low-SNR data.

3. Theoretical Background: Three-Dimensional Migration Methods.

A migration algorithm is applied to a dataset in order to reposition recorded energy to its true subsurface origin point. In performing such an operation the Fresnel zone of a wavelet (i.e., the area of the subsurface that contributes to the reflection) is made smaller, hence the effect of migration is to sharpen the focus of the subsurface image (Yilmaz, 2001).

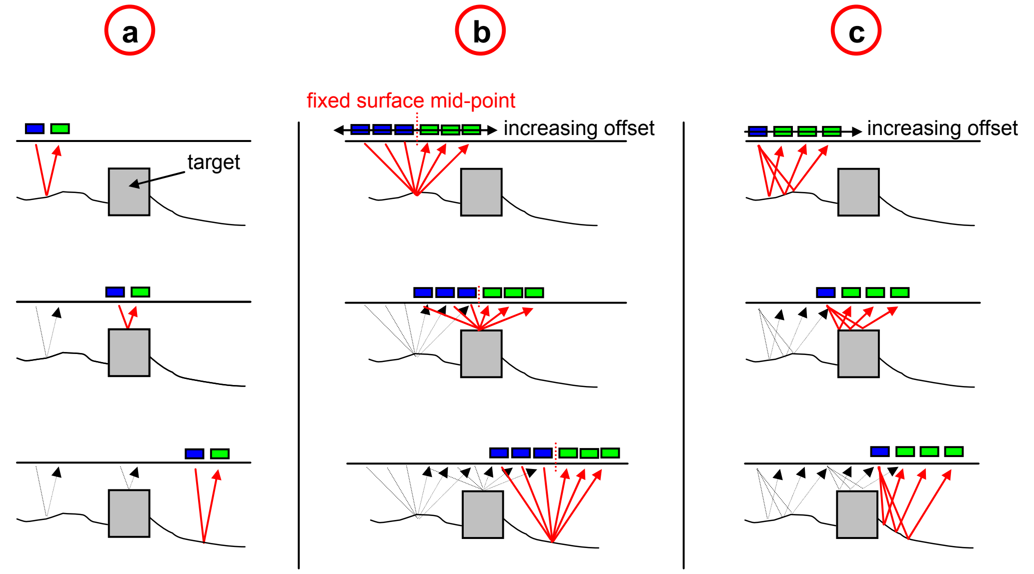

Figure 1 – Schematic diagrams of GPR acquisition, using common offset (CO), common mid-point (CMP) and common source (CS) antennae configuration. Each schematic shows data acquisition at three surface locations. The blue box represents Tx, the green box Rx; the grey square represents a subsurface target (e.g., an archaeological wall). Red arrows show raypaths of energy transmitted from Tx, black arrows show ray coverage from the previous acquisitions to convey increasing sample density; note that only the reflections from the shallowest subsurface interface are shown, for clarity. ***a)*** CO configuration. ***b)*** MO acquisition by CMP acquisition. ***c)*** MO acquisition by CS configuration.

Where GPR data are to be migrated, the migration algorithm is typically applied in a two-dimensional (2-D) sense, along the direction of the acquisition line. As such, only energy that is reflected or diffracted in the plane of the acquisition line can be correctly migrated. Energy originating from out of the plane of the acquisition line is incorrectly migrated, and may represent a source of noise that would degrade the 2-D migrated image. Recently, research has investigated the application of three-dimensional (3-D) migration algorithms to a GPR dataset. In performing a 3-D migration, energy that originates from both in and out of the plane of the acquisition line may be correctly migrated. Criteria for the fulfilment of 3-D acquisition parameters are provided in Grasmueck *et al.* (2005).

4. Introduction to Groundwell Ridge

Romano-British archaeology was discovered in 1996 at Groundwell Ridge, a developing housing estate just north of Swindon. Geophysical surveys by English Heritage provided evidence of extensive habitation at the site, and subsequent excavation suggested that settlements were of a high-status nature (Linford and Linford, 2004). One villa in particular was targeted with earth resistance, magnetometric and GPR survey methods. Representative GPR data are presented as a timeslice in Figure 1a, together with an interpretation in Figure 1b; note that the interpretation includes trends derived not only from the GPR dataset, but additionally from the earth resistance and magnetometer data. GPR data were acquired using a Sensors & Software *pulseEKKO1000* system, equipped with antennae of centre frequency 450 MHz, within a grid sampled at 5×50 cm^2 resolution. This villa serves as a suitable target for demonstrating the efficacy of the 3-D and MO methods for the following reasons.

a) the geometry of the building is structurally complex. Walls have vertical dip angles, and the rectilinear layout of Roman construction provides large local variation in target strike. As such, the improvement to the image of the villa should be considerable when deploying a 3-D acquisition strategy.
b) Data quality over the northern half of the building is lower, and reflectivity is more difficult to interpret, than over the southern half. A zone of reduced signal levels provides a location to trial the boosting of SNR by application of the MO method.
c) From a wider point of view, if 3-D and MO methods can be shown to improve data quality over an archaeological target, it is highly likely that they can be successfully deployed for other, less-complex, survey environments.

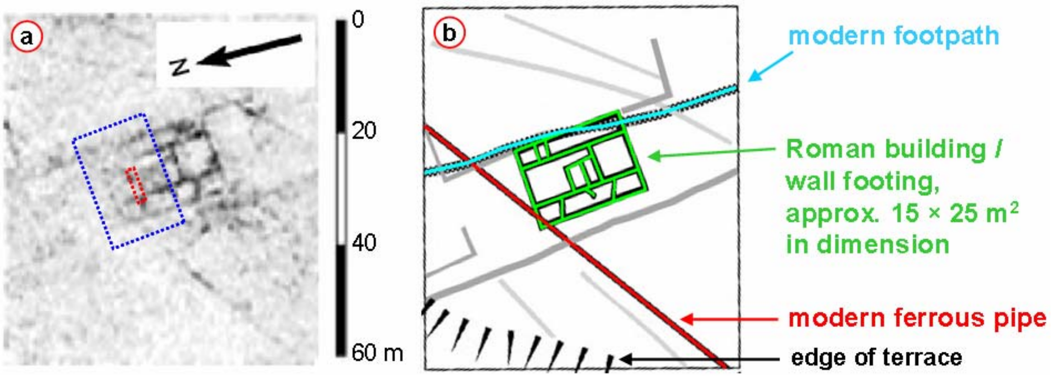

Figure 2 - GPR time slice and geophysical interpretation of a Romano-British building at Groundwell Ridge (Linford and Linford, 2004). ***a)*** 450 MHz GPR timeslice at 16-18 ns (≈ 60 cm depth), acquired with Sensors & Software *pulseEKKO1000* equipment. Sample grid is 5×50 cm^2, with survey lines orientated east-west. The blue box shows the extent of the CO grid, the red box the MO grid, for the data acquired for this report (see Section 4). ***b)*** Multi-geophysical interpretation, from Linford and Linford, 2004.

5. Spring 2006 GPR Acquisition

GPR data were acquired using a Sensors & Software *pulseEKKO1000* system, borrowed from the Geophysical Equipment Facility of the Natural Environment Research Council. As per the recommendation of Linford and Linford (2004), antennae of nominal centre frequency of 450 MHz were used. The location of the survey grids for the Spring 2006 acquisition are presented in Figure 2a; the CO grid is shown in outlined in blue, the MO grid in red. Representative data obtained at the site suggested, according to the method of Grasmueck *et al.* (2005), data should be acquired using a spatial stepsize, along and between profiles, no greater than 5 cm. A CO grid (blue outline in Figure 2a) was acquired over the northern half of the villa. The dimension of this grid is 21 × 14 m^2. Surveying was completed in approximately 9 days, over which repeat CMP acquisitions were made in order to monitor time-variant change in GPR reflectivity (e.g., due to overnight rain, or after a particularly hot day). A basic processing flow was applied to the CO dataset such that data could be plotted and an MO grid designed to sample an area of particularly low SNR. Such an area was identified, and a short section of an internal wall was surveyed with the MO methods (red outline in Figure 2a). As with the CO data, the spatial stepsize of Tx and Rx was again 5 cm. Since Tx and Rx are incremented by the same amount, the resulting CMP spacing is equal to half of that increment (Yilmaz, 2001); accordingly, the final grid resolution of the MO dataset is 2.5 × 5 cm^2. A further 9 days was required to acquire this grid. Full acquisition parameters for the Spring 2006 survey are detailed in Table 1.

	Grid area (m^2)	Nominal Freq. (MHz)	Tx stepsize (cm)	Rx stepsize (cm)	Min / Max offset (cm)	Fold of cover (%)	Grid resolution (cm^2)
CO grid	21 × 14	450	5	5	20	100	5 × 5
MO grid	8 × 1.4				20 / 235	2200	2.5 × 5

Table 1 – Acquisition parameters for GPR grids in the Spring 2006 Groundwell Ridge survey.

6. Data Processing

GPR data were processed primarily using the Landmark Graphics Corporation software *ProMAX* ™. Some data pre-processing was performed using Mathworks *MATLAB*® and the KJ Sandmeier software *ReflexW*©. A CO processing strategy varies significantly from an MO processing strategy, primarily by a stage of velocity analysis, normal move-out (NMO) correction and CMP stacking for the latter case; otherwise, processing for both datasets included conventional GPR enhancement techniques (e.g. frequency filtering, amplitude recovery). Data were desampled in order to simulate an acquisition performed with more routine spatial sampling criteria (i.e., 5 × 5 cm^2 desampled to 5 × 50 cm^2); this allows a direct comparison of the efficacy of a 3-D sampling regime versus a conventional 2-D approach, as used to create the timeslice in Figure 2a. Likewise, each dataset was migrated using 2-D and 3-D migration methods such that both could be compared to unmigrated data.

7. Survey Results, and Discussion

Figure 3 shows representative timeslices from the Spring 2006 acquisition, representing increasing complexity of acquisition across the columns, and increasing complexity of processing down rows. The least complex regime is represented by the upper-left timeslice, comprising unmigrated CO data sampled at 5 × 50 cm^2. Conversely, the most complex regime is represented by the lower-right timeslice, comprising MO data to which a 3-D migration algorithm has been applied. Timeslices (produced using the Schlumberger software *Petrel*) are extracted from the dataset at 19 ns, corresponding to an approximate depth of 65 cm beneath the ground surface. Explicitly, those timeslices represent:

a) CO GPR acquisition, sampled at 5 × 50 cm^2; data unmigrated.
b) CO GPR acquisition, sampled at 5 × 50 cm^2, data 2-D migrated.
c) CO GPR acquisition, sampled at 5 × 50 cm^2, data 3-D migrated.
d) CO GPR acquisition, sampled at 5 × 5 cm^2, data unmigrated.
e) CO GPR acquisition, sampled at 5 × 5 cm^2, data 2-D migrated.
f) CO GPR acquisition, sampled at 5 × 5 cm^2, data 3-D migrated.
g) MO GPR acquisition, overlying 5 × 5 cm^2 timeslice, data unmigrated.
h) MO GPR acquisition, overlying 5 × 5 cm^2 timeslice, data 2-D unmigrated.
i) MO GPR acquisition, overlying 5 × 5 cm^2 timeslice, data 3-D unmigrated.

Target resolution in the coarsely sampled datasets (Figures 3 a, d and g) is always less that that observed in the finely sampled datasets (Figures 3 b, e and h). Clearly, the target archaeology is more visible in Figure 3b than in Figure 3a; the finer sampling of the subsurface in the former dataset allows features that are running slightly obliquely to the east-west acquisition to be more completely imaged. Application of a 2-D migration strategy to these datasets (Figures 3 d and e) does little to improve target resolution compared to the unmigrated data given the complex, 3-D nature of the archaeological target. When 3-D migration is applied to coarsely sampled data (Figure 3g) the algorithm fails, and only energy reflected from features that strike orthogonally to the survey lines (i.e., north-south) is correctly migrated. By comparison, 3-D migration of finely sampled data (Figure 3h) yields a subsurface image with excellent spatial resolution. Where MO data (Figures 3 c, f and i) are compared to co-located CO data, SNR within the MO grid is much higher. Other than the north-south wall towards its western extent, amplitudes in that section of CO data are low and there appears to be very little reflectivity. Where MO methods are applied, it becomes clear that there is also a wall, running east-west, at the southern extreme of the MO grid. As expected from inspection of the entire CO grids, resolution should increase considerably where 3-D migration is applied to adequately sampled data. Resolution is indeed improved on application of 3-D migration (Figure 3i); the hypothesis that combined 3-D and MO sampling strategy greatly improves subsurface image quality appears therefore to have been verified. Enlargements of the MO grids, and co-located sections of the CO grids are shown for clarity in Figure 5; specifically, timeslices show:

a) CO GPR acquisition, sampled at 5 × 5 cm^2, data unmigrated.
b) CO GPR acquisition, sampled at 5 × 5 cm^2, data 3-D migrated.
c) MO GPR acquisition, sampled at 2.5 × 5 cm^2, data unmigrated.
d) MO GPR acquisition, sampled at 2.5 × 5 cm^2, data 3-D migrated.

8. Further Work

The large amount of data collected at Groundwell Ridge opens up many research avenues which will be investigated in the coming months. Several research questions present themselves, including:

1. Many more processing algorithms are applicable to MO data than have currently been used (e.g., demultiple algorithms, pre-stack migration), all of which could potentially improve SNR. How much further can SNR be boosted, and at what processing expense?
2. Fine sampling of a wavelet, in accordance with Grasmueck *et al.* (2006), is particularly laborious especially where spatial sampling criteria suggest the use of a small Δx (e.g., the 5 cm criteria used in this survey). How closely must those criteria be matched in order that 3-D migration provides an improvement to the unmigrated image of the subsurface? Can trace interpolation be used to predict the waveforms in 'unsampled' traces where Δx is exceeded, thereby facilitating 3-D migration?
3. Currently, improvement to SNR is assessed on a qualitative basis alone. Is there a means of *quantifying* improvement to SNR and resolution? One possible method would be some measure of the stack power within a timeslice, in-line or cross-line.

9. Forthcoming Publications

We envisage presentation of this work in the journal 'Archaeological Prospection', with the theoretical elements of data interpolation potentially submitted to 'Journal of Applied Geophysics' or 'Near Surface Geophysics'.

10. Acknowledgements

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11. References

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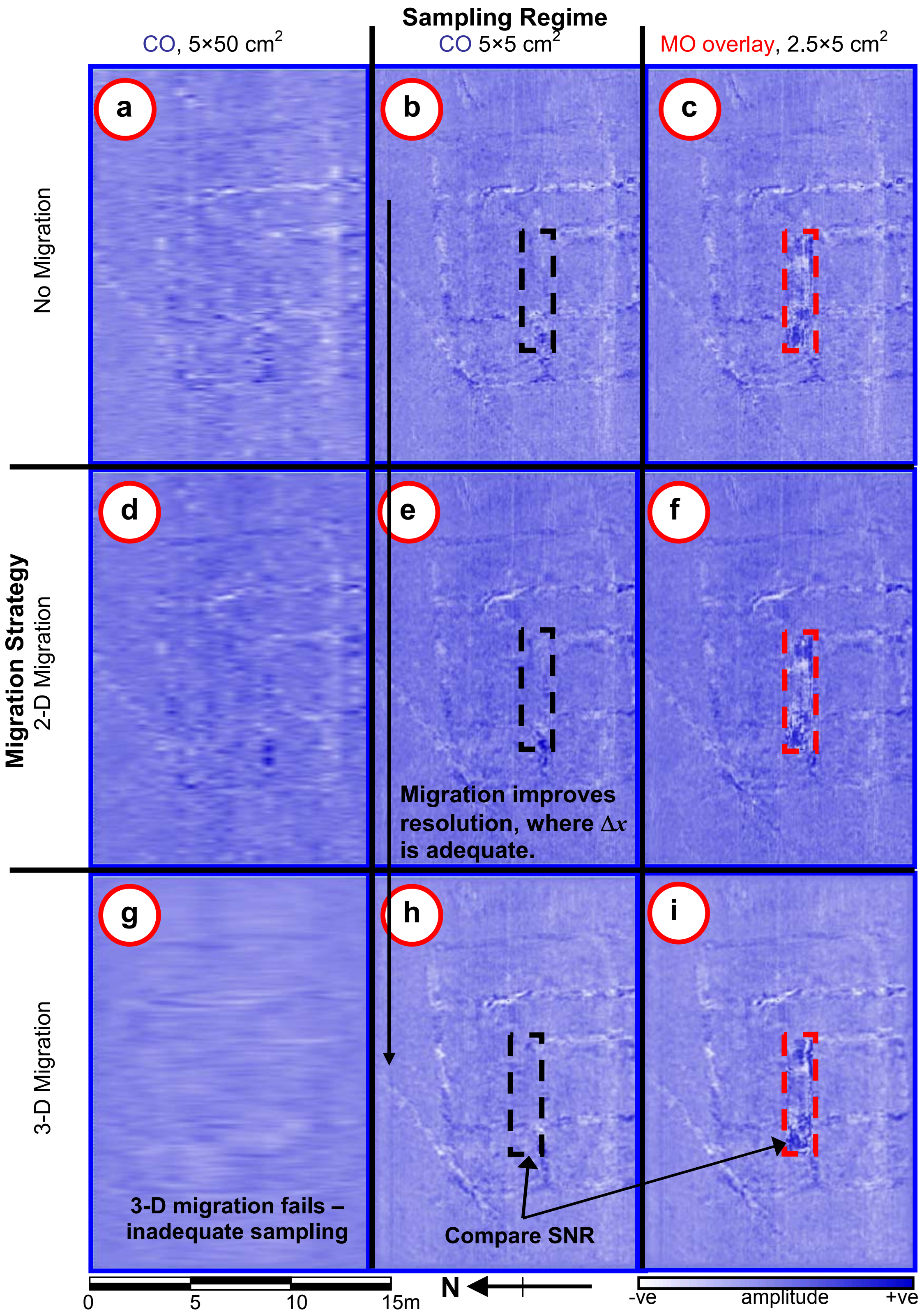

Figure 3 – Representative timeslices from the Spring 2006 GPR acquisition at Groundwell Ridge. Complexity of acquisition increases from right to left, complexity of migration regime increases from top to bottom. Details of each timeslice are provided in the main text of this report.

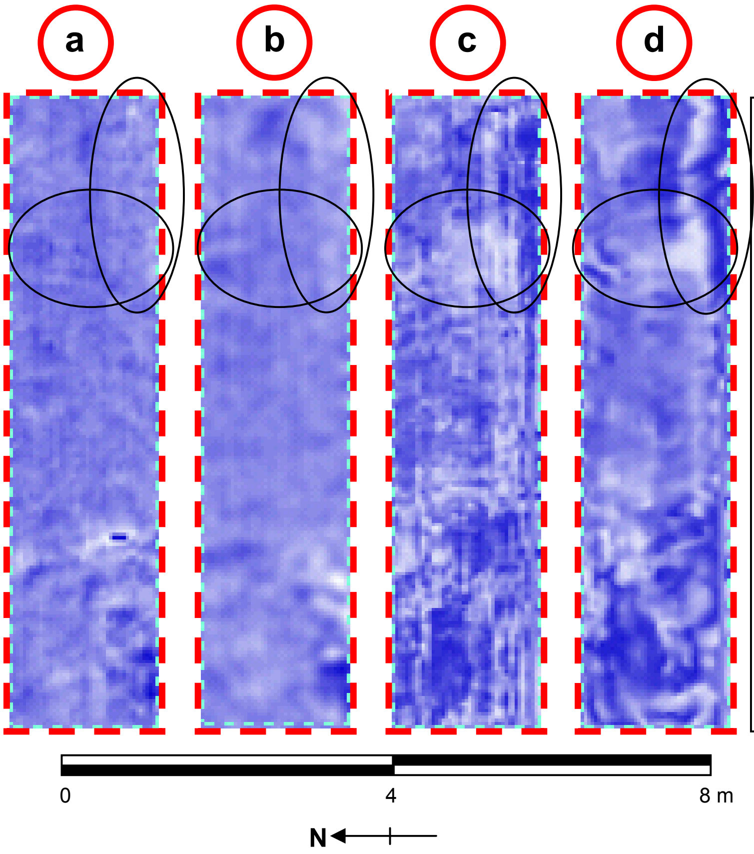

Figure 4 – Enlargements of co-located CO grid section and MO grid from the timeslices in Figure 6. Note specifically the improvement to SNR in the circled areas. Apparent reflectivity is low in the CO datasets (unmigrated in a, 3-D migrated in b), whereas a north-south wall with an adjoining east-west feature becomes obvious in the MO datasets (unmigrated in c, 3-D migrated in d). Reflectivity appears in the MO dataset because of the increase in SNR resulting from the use of the MO technique.