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Ground-penetrating Radar Imaging of Twelfth Century Romanesque Foundations Beneath the Thirteenth Century Gothic Abbey Church of Valmagne, France

SUWIMON UDPHUAY[1]*, VIVIAN L. PAUL[2], MARK E. EVERETT[1] AND ROBERT B. WARDEN[2]

[1] *Department of Geology and Geophysics, Texas A&M University, USA*
[2] *Department of Architecture, Texas A&M University, USA*

ABSTRACT Ground-penetrating radar surveys with closely spaced profiles using 500- and 800-MHz antennae were performed on the fine gravel floor of the Gothic abbey church of Valmagne, near Montpellier, in south-central France. The accessible floor area of the choir, transept and nave was surveyed to locate and preliminarily interpret the remains of the twelfth century Romanesque building beneath the existing building. Processed two-dimensional ground-penetrating radar profiles and constructed time-slice images show distinct reflection events associated with the twelfth century foundations. The GPR technique is calibrated against a known buried limestone pier belonging to the earlier Romanesque construction. It proved challenging to differentiate the remains of the twelfth century building from the existing building and the host geology because the dielectric contrasts between them is low. Preliminary interpretation of the results suggest that the Romanesque pier abuts and continues under a thirteenth century pier at the intersection of the ambulatory and transept of the existing church. In addition, the twelfth century building appears to have had a rectangular sanctuary flanked by chapels of unequal width opening off a transept comparable in width and length with the existing transept and a nave comparable in length with the existing nave. The results of this study are significant to medieval architectural history since they reveal new subsurface constraints on the nature of Cistercian construction in Languedoc.

Key words: ground-penetrating radar; Gothic architecture; Romanesque architecture; medieval; Cistercian

Introduction

The Cistercian abbey of Valmagne (Figure 1), located southwest of Montpellier, is one of the best preserved medieval Cistercian complexes in the Languedoc region of south-central France. The abbey appears to have been founded as an independent Benedictine 'reform' house ca. 1138 but by 1162 the monks of Valmagne had affiliated themselves to the Cistercians (Berman, 2000, pp. 205–208). The abbey was abandoned when it was sacked during the 1789 French Revolution. In 1791, the abbey was sold by the French government to a private citizen who adapted the church for wine production and installed huge barrels for aging wine in the aisles of the nave, in the transept arms and in each of the ambulatory chapels. Considerable restoration has been carefully carried out by the present owner, who opened the abbey to the public in 1975. The structure is architecturally significant for its position within the development of both Cistercian and Gothic architecture in Languedoc (Paul, 1982).

Of the existing buildings, most of the conventual buildings and the refectory/dormitory of the lay brothers or *conversi* clearly date to the twelfth century. Portions of the cloister are twelfth and thirteenth century, with later rebuildings. The existing Gothic church is thirteenth and fourteenth century and follows what may be called a 'cathedral' plan, that is, tall for a Cistercian building, with an ambulatory, radiating chapels and flying buttresses. For details, see the plan of the church, showing its various periods of construction, in Figure 2a. The known layout of the

* Correspondence to: S. Udphuay, Department of Geological Sciences, Chiang Mai University, Thailand.
E-mail: suwimon@chiangmai.ac.th

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Figure 1. Interior of the Abbey Church of Valmagne, looking eastward. This figure is available in colour online at wileyonlinelibrary.com.

twelfth century building is shown by the heavy black lines in Figure 2a; these are labelled as XII in the figure legend.

Of the twelfth century Romanesque church, little other than portions of the south transept wall of the existing building and perhaps portions of the wall of the existing south aisle, could be securely identified. This changed when remnants of two twelfth century piers were discovered in the south arm of the existing transept during a general survey of the abbey. The discovery of these twelfth century remnants raises a number of important questions. What, for instance, was the character of the twelfth century building? To what extent did it reflect either local construction practices or characteristics that have come to be associated with Cistercian construction? Answers to these questions would add considerably to an understanding of the early years not only of Valmagne but of Cistercian construction in Languedoc. Then, what was the relationship between the twelfth and the thirteenth century churches? The likelihood is that the earlier building would have had an impact on the plan, siting and campaigns of construction for the later building, but the extent of this impact cannot be evaluated without more information concerning the twelfth century building. This requirement, plus the facts that Valmagne has never been systematically excavated and the complexity, time and expense that would be involved in mounting an organized programme of excavations combined to suggest a ground–penetrating radar (GPR) survey. It was hoped that the GPR images could provide partial or complete answers to the aforestated questions. The main goal of this paper is to describe and intepret a comprehensive GPR survey of the interior of the abbey church of Valmagne and to explain how the results advance our understanding of its construction history. Although the application of GPR techniques to historical structures as presented herein is not strictly new, the analysis and processing methods used to extract information from the data constitutes an original contribution to archaeological prospection.

A GPR survey of Valmagne, in fact, offers an unusual opportunity. Although GPR has become in the past two decades an important method in archeological exploration (e.g. Vaughan, 1986; Bevan, 1991; Goodman and Nishimura, 1993; Goodman *et al*., 1995, 2004; Conyers and Goodman, 1997; Gracia *et al*., 2000; Leckebusch, 2003; Piro *et al*., 2003; Leucci, 2006; Barone *et al*., 2007; Gustafsson and Alkarp, 2007) and is well-suited to investigating the foundations of buildings with archaeological significance, the number of instances in which it has been used on the interior of an extant building, especially a medieval building, is less common (Dabas *et al*., 2000; Leckebusch, 2000; Leucci, 2002; Neubauer *et al*., 2002; Tsokas *et al*., 2007). A GPR survey of Valmagne might reveal and offer solutions to problems peculiar to the conditions represented by the building's unique subsurface conditions. The remains of a twelfth century pier (Figure 2b), first discovered at the southeast entrance to the ambulatory in 1998, can be used to determine the characteristic GPR signature of subsurface foundations. In this paper we show that, along with some important successes, the GPR survey actually raised several new questions. Radar imaging of the earlier foundations was in fact particularly challenging due to the very low dielectric contrast between the host carbonate-derived soil and the limestone foundations. The twelfth and thirteenth century remains are both dry limestone of similar provenance so it was not possible always to differentiate between twelfth and thirteenth remains.

Overviews of GPR fundamentals and time-slicing techniques in archaeology can be found in Vaughan (1986), Goodman *et al*. (1995), Malagodi *et al*. (1996), Conyers and Goodman (1997) and Conyers (2004).

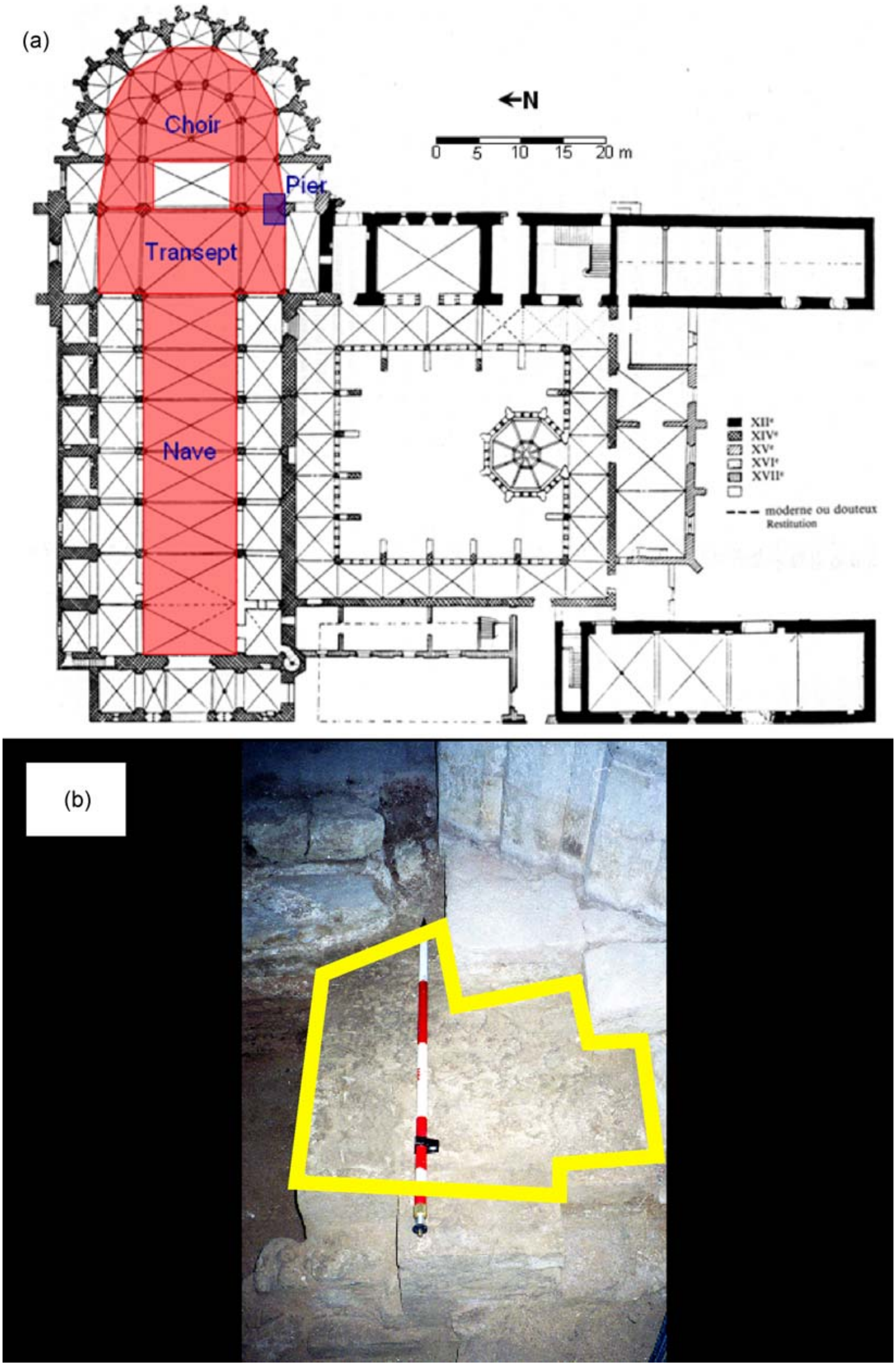

Figure 2. (a) Plan of the Gothic church, highlighting in red the areas of the nave, transept and choir corresponding to the GPR survey. The Roman numeral labelling indicates the century of construction of the various parts of the church. The area highlighted in blue on the church plan indicates the previously located buried limestone Romanesque pier (shown in (b)). The exposed twelfth century limestone pier is outlined in yellow in (b). This figure is available in colour online at wileyonlinelibrary.com.

Site description and data acquisition

The abbey of Valmagne, like most Cistercian buildings, was strategically built near a source of water on a site that offered excellent opportunities for agricultural development. In the case of Valmagne specifically, this site was only a few kilometres from the old Roman *via domitia* in an area where Roman villas are known to have existed. Stone for the construction of the abbey church was quarried locally. A geological report commissioned by the current owner of the abbey determined that the stone used in the construction of the church came from two local quarries: one quite close to the actual building site and the other located between the abbey and Mèze (Diane d'Allaines, personal communication).

Data were acquired using 500 and 800 MHz antennae with line spacing 0.25 m on the fine gravel floor installed by the present owner. The portions of the church surveyed by the GPR are shown as the red and blue regions in Figure 2a. Inaccessible areas that could not be surveyed correspond to the locations of existing piers, a temporary rectangular stage at the entrance to the choir (shown as the white rectangle in Figure 2a) and those areas of the aisles, transept and ambulatory chapels obscured by the large wine barrels installed in the nineteenth century. The two-dimensional GPR profiles were acquired using a shielded antenna RAMAC system manufactured by Malå GeoScience. Figure 2b shows the excavation of a twelfth century limestone pier; its location within the church plan is indicated by the blue rectangle. The same area is outlined by the red oval in Figure 3, which also shows GPR data being acquired.

Figure 3. Ground-penetrating radar data acquisition over the Romanesque limestone pier. The red oval indicates the location of the buried pier. The floor shown in this photograph corresponds approximately to the blue rectangular region indicated in the previous figure. This figure is available in colour online at wileyonlinelibrary.com.

Data processing

Although unprocessed GPR data often yield fairly good quality subsurface images, the data may be difficult to interpret. Enhanced processing can improve both spatial and temporal resolution, as well as image clarity. The GPR data from Valmagne were stored in the seismic standard SEG-Y format and processed using seismic reflection software commonly used in the oil and gas exploration industry, as in Udphuay (2004). The GPR data were processed using the ProMAX® package from Landmark Graphics. ProMAX® provides several advantages over commercial GPR software packages as it contains *f–k* migration, edge detection and seismic coherency (Marfut *et al.*, 1998) tools, all of which were used in this study. Although ProMAX® is a powerful processing package, a fairly steep learning curve must be overcome for archaeologists to become familiar with advanced data processing methods of exploration geophysicists.

The following processing sequence was adopted in this study: de-wow, first-arrival time alignment, background subtraction, amplitude recovery and filtering. High-pass de-wow filtering removes a time-dependent low-frequency coherent noise called *wow* that causes amplitude distortion within each data trace. Wow is due to a number of effects, including the saturation of the receiver electronics by the very high-amplitude source signal (Gerlitz *et al.*, 1993). The presence of wow results in an amplitude bias such that GPR traces have a non-zero mean. A GPR trace is a series of radar reflections recorded at one station on the ground. After de–wow filtering, a first-arrival time alignment was applied to correct and align the first arrival times of the GPR traces to an arbitrary horizontal datum (zero depth). Time offset due to instrument recording and antenna separation was corrected. A simple background subtraction procedure was then applied to remove clutter caused by the presence of the ground surface. An amplitude recovery procedure was then used to compensate for effects of spherical wave divergence, scattering from small heterogeneities and GPR signal attenuation. The amplitude recovery process enhances the signal-to-noise ratio, especially in the deeper section of the GPR profiles. Bandpass frequency filtering was then applied to remove frequencies interfering in the two-dimensional profiles by passing a specified range of dominant signal frequencies. The effect of the bandpass filter is to enhance the signal-to-noise ratio.

Stolt *f-k* migration (Landmark Graphics Corporation, 2003) from the ProMAX® package was then

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used on the two-dimensional data sets to focus and reposition reflected events to their true spatial and temporal position.

A radar event is defined herein as a high-amplitude reflection. The migration velocity was estimated from the shapes of diffraction hyperbolae. By migrating the data with various constant velocities, a velocity of $0.12\,\mathrm{m\,ns^{-1}}$ best collapsed the hyperbolae without producing 'smiles'. This value of velocity falls within the range found in similar environmental and geological environments (Dabas *et al.*, 2000; Gracia *et al.*, 2000; Leckebusch, 2000; Barone *et al.*, 2007) and is used throughout the paper to convert times to equivalent depths on radar sections.

After the two-dimensional processing was complete, the two-dimensional GPR profiles from each of the surveyed areas were combined into individual three-dimensional volume data sets. The three-dimensional processing was initiated by applying the seismic coherency technique (Marfurt *et al.*, 1998), after which horizontal squared-amplitude time–slice maps were created. Seismic coherency is a measure of lateral changes in the seismic response related to geological changes. The technique computes the dissimilarity between adjacent traces, highlighting lateral seismic changes that often relate to geological changes such as faults, structural and stratigraphic features and other geological patterns. These geological changes often stand out as prominent reflections that are readily interpreted. The seismic coherency technique is applied to archaeological GPR data to better image and identify locations of buried cultural remains and related stratigraphy. Sassen and Everett (2009) have developed a new polarimetric coherency algorithm for vector GPR data but its application is beyond the scope of the present article.

In archaeology, time-slice maps often have been used to provide information to identify the size, shape, depth and location of buried cultural features (Goodman and Nishimura, 1993; Piro *et al.*, 2003; Conyers,

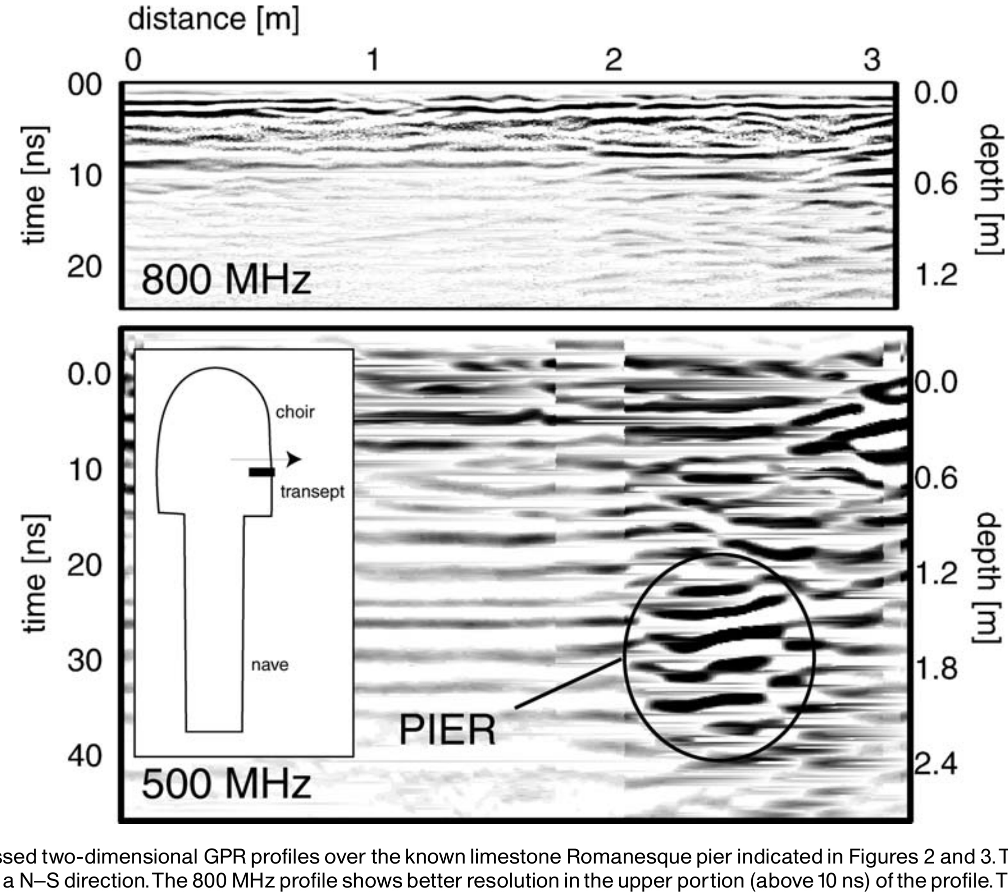

Figure 4. Processed two-dimensional GPR profiles over the known limestone Romanesque pier indicated in Figures 2 and 3. The two profiles are coincident and in a N–S direction. The 800 MHz profile shows better resolution in the upper portion (above 10 ns) of the profile. The 500 MHz profile shows deeper reflections greater than 10 ns. The reflection at about 25 ns of the 500 MHz profile is the signature of the pier. In all GPR sections, the time is two-way travel time and depth is converted from time using $0.12\,\mathrm{m\,ns^{-1}}$ velocity. The map locations of the profile are indicated by the heavy black lines on the inset church plans and the directions of the GPR profiles are indicated by the arrows.

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2004; Goodman *et al*., 2004). Areas of low-amplitude reflections usually indicate uniform matrix material or homogeneous soils, while those of higher amplitude denote zones of high electrical subsurface contrast owing to buried archaeological features, voids, or stratigraphic changes. Time-slice maps were created over $\Delta t = 5$ ns two-way traveltime intervals to represent the amplitude plan-view distribution at every ~0.3 m depth below ground surface.

Data interpretation

The GPR data at Valmagne are presented as both depth sections and time-slices. The latter are defined herein as horizontal slices, at a constant two-way travel time, which show reflection amplitudes, and which are converted to depth using the migration velocity.

Depth sections

Shown in Figure 4 are N–S aligned GPR depth sections, at both 500 and 800 MHz frequencies, which probe the known twelfth century Romanesque limestone pier (shown earlier in Figure 3). The GPR reflection from the pier stands out distinctly on the right portion of the 500 MHz profile. However, a corresponding reflection does not appear as clearly on the 800 MHz profile due to lower signal penetration. The time window of the 800 MHz profile in Figure 4 is in any case too small to show the reflection of the pier. The fact that Figure 4(top) is featureless is important since it justifies using the 500 MHz radar instead of the 800 MHz radar.

The GPR depth sections that cross the centre of the transept area in a west–east direction are shown in Figure 5. The dipping feature in the middle of the 500-MHz profile at ~7–10 ns may represent buried steps leading upward to the choir area. Since the same

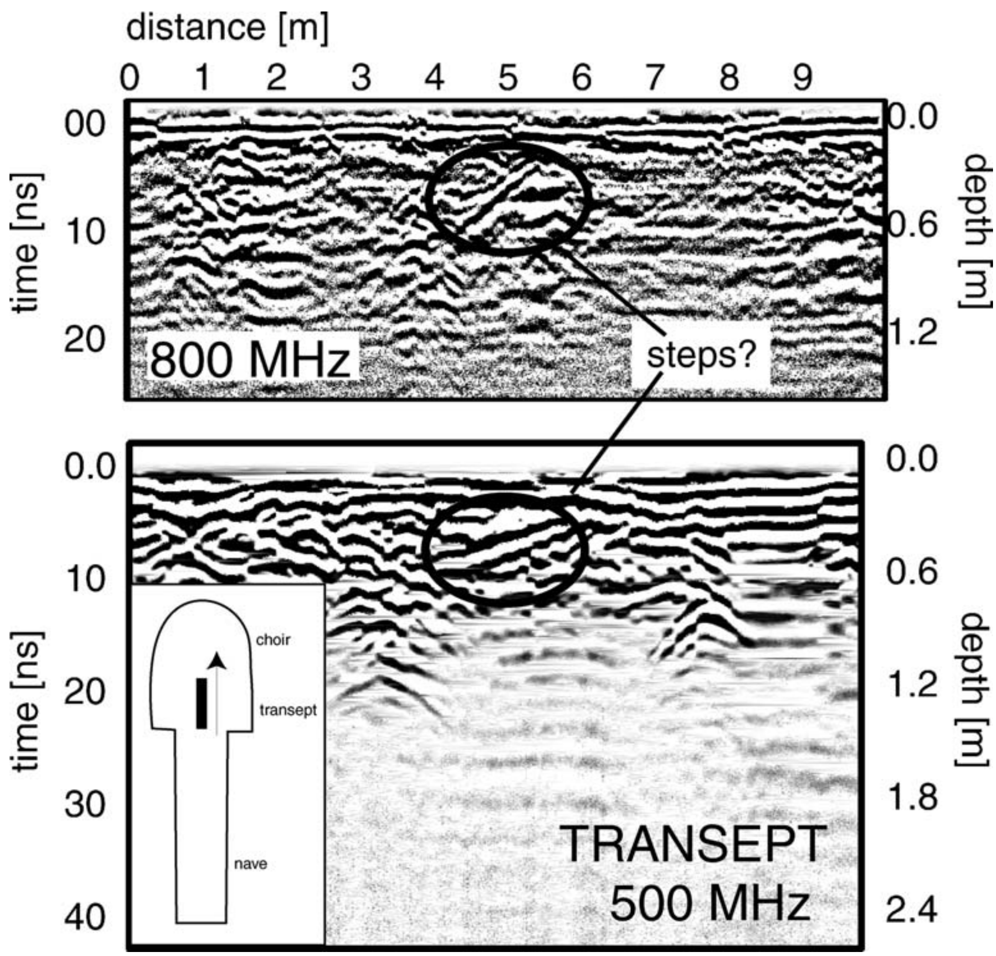

Figure 5. Processed two-dimensional GPR profiles of the transept area. The two profiles were taken at the same location at the middle of the transept. The 800 MHz profile shows higher resolution above 10 ns but contains less penetration of reflection energy than the 500 MHz profile. A distinct dipping reflector is found in the middle of both profiles. This may represent an ancient step going up into the choir.

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dipping feature is seen clearly in the 800 MHz data, the steps are probably more shallowly buried than the twelfth century pier. All of the interpretations in this paper are based on the apparent depth of the radar feature, which is found using the subsurface velocity 0.12 m ns^{-1} determined from the migration analysis.

An east–west radar section at 500 MHz along the centre of the nave is shown in Figure 6. A line of prominent hyperbolic reflectors is apparent, especially between stations 10–20 and 40–44 at $\sim$10–20 ns; this depth section provides a good example of the large number, excellent visibility, and consistency of GPR reflections that have been imaged in the subsurface of the church. Similar east–west radar sections crossing the choir area are shown in Figure 7. The distinctive hyperbolic events at $\sim$10–20 ns are interpreted to be caused by reflections from buried twelfth century and collapsed Roman villa walls. Support for this interpretation comes from analysis of the time-slices.

Time slices

Figure 8 presents GPR time-slices of the pier area assembled from the 500 MHz data. A high-amplitude zone associated with the known buried Romanesque foundation begins to appear on the 20–25 ns time slice. The event is fully developed on the 25–30 ns and 30–35 ns time slices. The Romanesque foundation thus occupies a depth interval of 1.2–2.7 m beneath the surface. The other high-amplitude event, at the lower right side of the time slices, corresponds to the location of an existing Gothic pier. The late arrival of the reflections indicates a deep structure, suggesting that the Gothic pier may have been built atop pre-existing Romanesque foundations.

Comprehensive time-slices of the accessible floor area of the church are illustrated in Figures 9 and 10. Several provocative reflections have been numbered for further discussion and fall into three categories: (I) those that are not unusual in the context of a twelfth century Cistercian building and thus fairly easy to explain; (II) those that are problematic to interpret; and (III) those that are totally unexpected. Without actual excavations, however, the suggested identifications of the GPR signatures should be regarded as somewhat conjectural.

Category I events (1–6)

The first category includes the events labelled 1–6 on Figures 9 and 10. Their identification can be explained with relative certitude either because of shape or location or because they represent features that are not unusual in a twelfth century Cistercian building. The angle and direction of event 1, running diagonally across the transept, suggests a water conduit leading from the spring located northeast of the abbey toward the cloister fountain. Two north–south linear features running across the nave, labelled event 2, probably represent the buried remnants of screens that delimited the choirs of the lay brothers and the monks, as is common in Cistercian buildings.

The wide, high-amplitude swaths (event 3) running north–south near the entrances to the ambulatory are oriented perpendicular to the two existing square Gothic chapels. These events may also be seen as the disturbed zones between locations marked 04–06 m in the depth sections of Figure 7a and c. Based on direct visual observations of twelfth century portions of the south transept wall that are incorporated into the existing

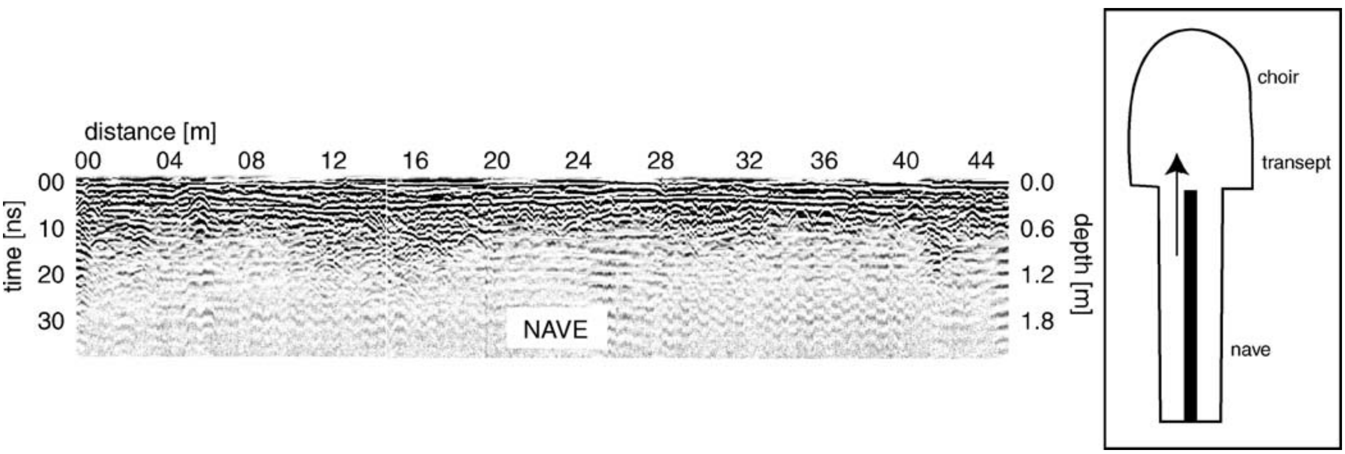

Figure 6. Processed two-dimensional 500-MHz profile of the nave area showing some distinct reflection events. The profile was taken in the middle of the nave and shows a continuous reflecting horizon from time 5–10 ns over a distance of 8–39 m.

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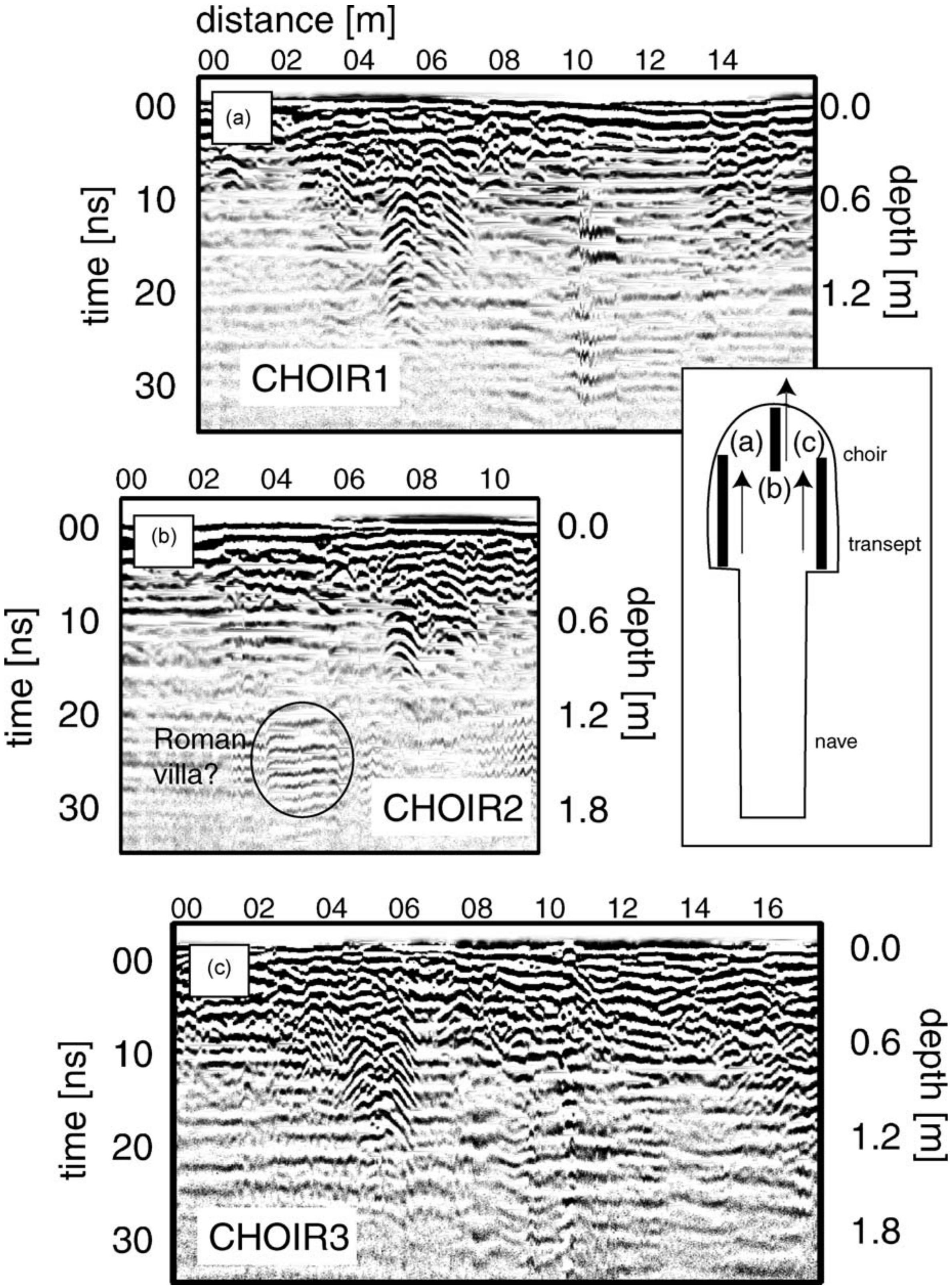

Figure 7. Processed two-dimensional profiles of the choir area showing some distinct reflection events.

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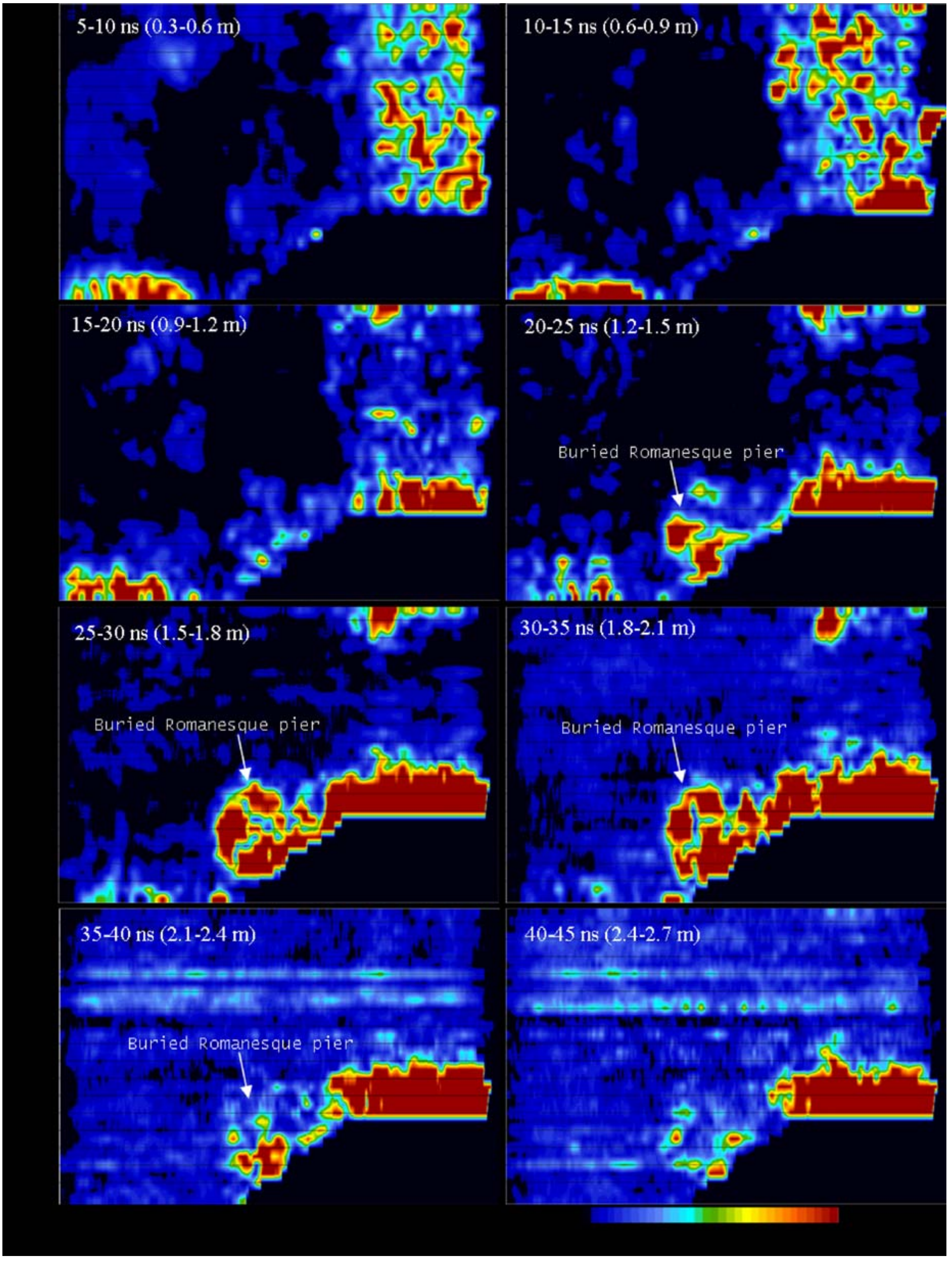

Figure 8. Time-slices integrated over 5 ns of the area where the Romanesque limestone pier is located. The GPR signature of the pier appears from the 20–25 ns time slice down to the 35–40 ns slice. Note that the black area in the bottom right corner of each time-slice represents those areas where GPR data could not be taken because of the existing Gothic pier (see Figure 3). This figure is available in colour online at wileyonlinelibrary.com.

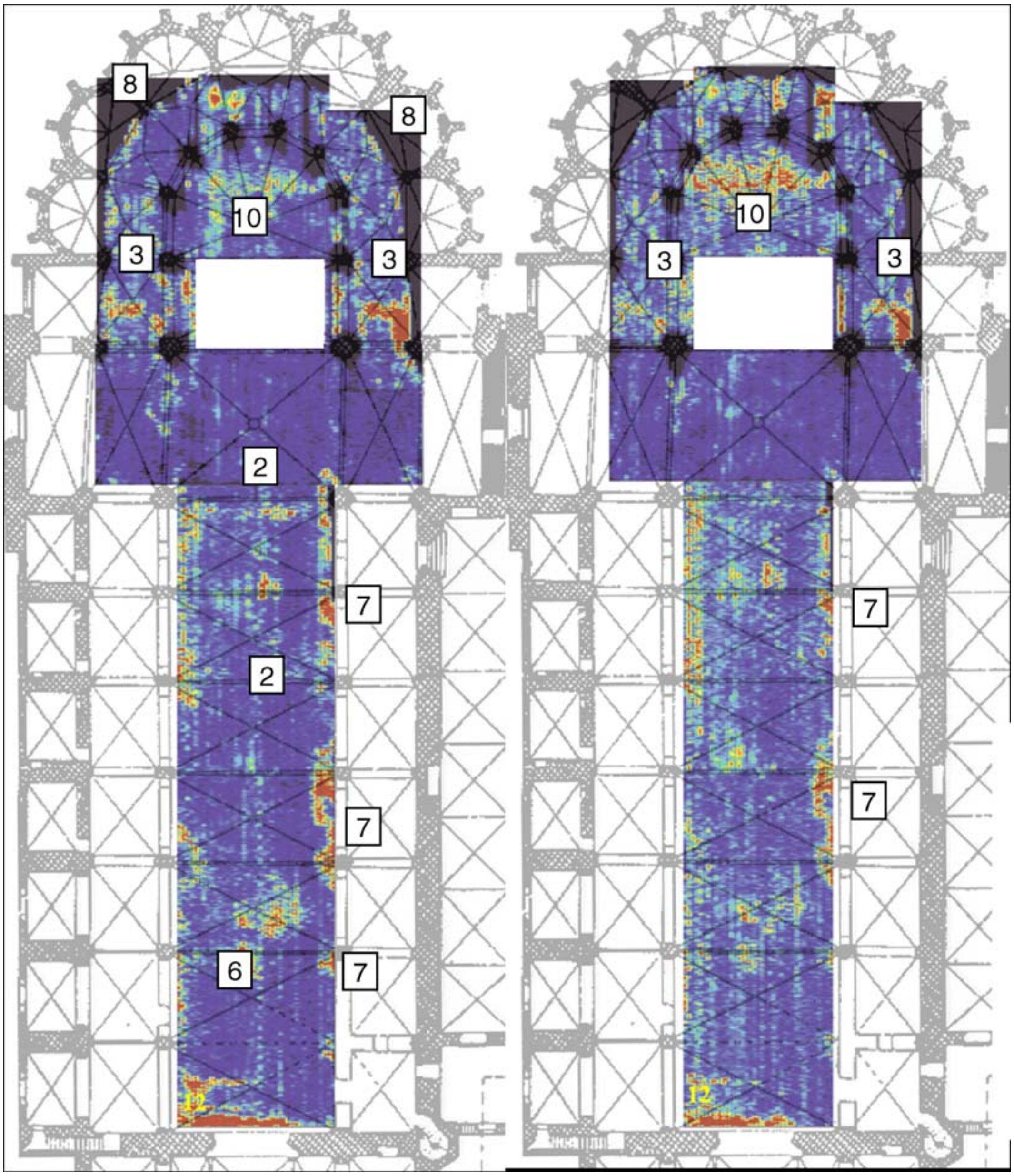

Figure 9. Combined GPR time-slices over the entire surveyed area. Each time-slice is the summation of squared amplitudes over a 5-ns time-window. High amplitude is indicated in red, low amplitude in blue, and zero amplitude or no data taken areas in black. The time to depth conversion uses estimated constant velocity of 0.12 m ns^{-1}. These time-slices are for times 15–20 and 20–25 ns, corresponding to 0.9–1.2 and 1.2–1.5 m depths. This figure is available in colour online at wileyonlinelibrary.com.

Gothic building, the swaths probably constitute the GPR signature of the foundations of a twelfth century Romanesque choir. The fact that no GPR signature is apparent in the choir space to the east of the stage area suggests that this earlier building may have had an abrupt rectangular eastern termination in the manner of many twelfth century Cistercian buildings.

The known twelfth century pier at the entrance to the Gothic ambulatory is labelled event 4. The location of this pier with reference to the presumed twelfth century remains (event 3) together with its distance to a second twelfth century Romanesque pier in the southeast corner of the transept, suggest that the twelfth century abbey church of Valmagne may have had a rectangular choir flanked on the north and south by chapels of unequal width opening off the transept. A similar plan is found in the twelfth century Cistercian abbey church of Fontfroide near

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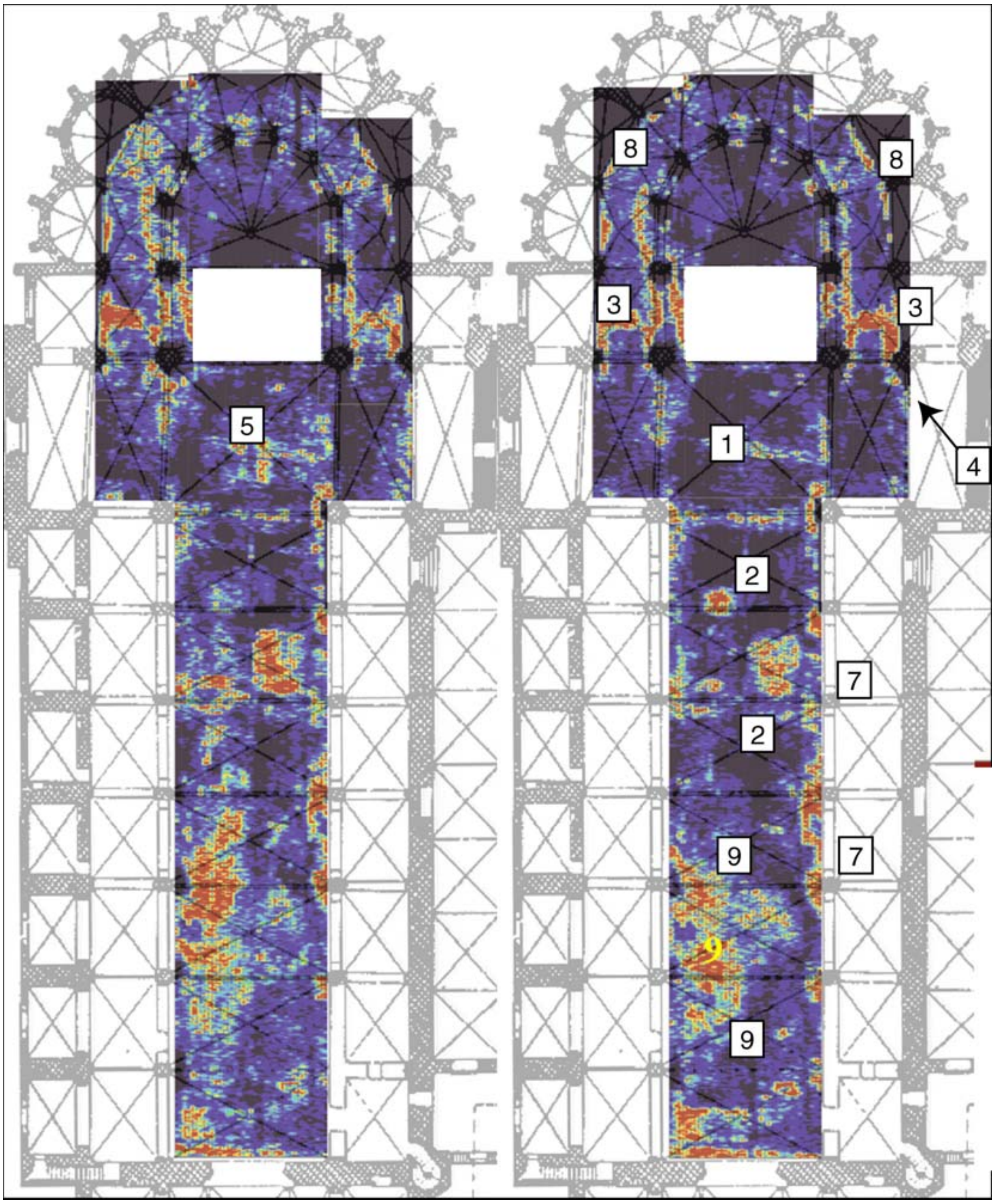

Figure 10. As in the previous figure, except showing 35–40 and 40–45 ns time-slices, corresponding to 2.1–2.4 and 2.5–2.7 m depths. This figure is available in colour online at wileyonlinelibrary.com.

Narbonne, a city located ~40 km to the southwest of Valmagne.

Two other first-category reflection events (5 in the transept and 6 in the nave) are readily explained in the context of a religious structure, and are likely to be tombs. Given their different depths, however, it is possible that event 5 represents a more recent burial, perhaps associated with the thirteenth century building, while event 6 is associated with the underlying twelfth century structure.

Category II events (7–9)

The second category of GPR events consists of those labelled 7–9. These are difficult if not impossible

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to interpret with certitude due to their unexpected physical locations. The difficulty in distinguishing between twelfth and thirteenth century subsurface features at Valmagne demonstrates both the strengths and weaknesses of a GPR survey of this sort, even when used in conjunction with known archaeological evidence and an understanding of local traditions of building. Since both the twelfth and thirteenth century buildings were constructed from dry limestone and thus have similar dielectric properties, the foundations of one building cannot always be distinguished from the other. Furthermore, the thirteenth century builders probably incorporated or used remnants of the twelfth building for the foundations. Event 7, running along the south side of the first four east bays of the nave, is a good example. A number of factors argue in support of a twelfth century date for this event. For example, the event aligns with putative twelfth century sanctuary walls on the south side of the Gothic choir. The weight of this and other evidence suggests that remains of the twelfth century building were used as foundations for the thirteenth century building, at least in this portion of the building, and that the twelfth century building was the same length as the existing Gothic building.

Reflection event 8 curves around the exterior of the ambulatory, cutting across the entrances to the radiating chapels of the thirteenth century Gothic building. This line is echoed by fainter reflections between the piers of the hemicycle. The faint reflections between the hemicycle piers can be comfortably identified as thirteenth century in date. A balustrade was intended to connect the Gothic hemicycle piers (plainly indicated on the pier bases of the hemicycle), and it is probable that the line between the hemicycle piers represents the base for that balustrade. The distinct GPR signature around the exterior of the ambulatory is frankly perplexing, and a case could be made for either a twelfth or thirteenth century date. It begins to appear at depths comparable with the known twelfth century pier, suggesting a twelfth century date. It resembles the foundation line of an ambulatory wall. This makes little sense with reference to a twelfth century building that is likely to have had a rectangular termination. Could it represent foundations for the Gothic ambulatory piers or steps into the Gothic chapels? At the present time we do not attempt to distinguish between these two possibilities. Event 8 proves that even a combination of GPR data and knowledge of medieval building practices is insufficient to clarify the nature of the subsurface reflections.

The prominent irregularly shaped event 9 in the nave area is also problematic. After careful thought, we feel it is best interpreted as rubble, a legacy from the long and varied history of the church over the past 600–700 years.

Category III event (10)

Event 10 in the choir belongs to the third category of totally unexpected and potentially exciting discoveries. Given the large depth of these reflectors, they may represent the collapsed walls of a Roman villa conjectured to have existed at the site. While the conjecture is somewhat speculative, Valmagne lies only a short distance from the Via Domitia and from a Roman villa located outside the nearby town of Loupian, so it would not be surprising if Roman remains were present at depth beneath the abbey. For comparison, the signature of the putative Roman villa in depth section format is seen as the disturbed zone in Figure 7b.

Conclusions and discussion

Ground-penetrating radar is a powerful geophysical investigation method for use in archaeology, especially in those areas where excavation is not allowed. Ground-penetrating radar can image near-surface buried objects with a very high resolution in areas where there is a sufficiently strong electrical impedance contrast of target subsurface objects and the host soil.

In this study, subsurface radar imaging was particularly challenging due to the low contrast between potential twelfth century remains and the host soil. Careful data processing using standard techniques developed in exploration seismology proved useful to exploit the subsurface information. In this study, the GPR data were processed using the ProMAX® package from Landmark Graphics. ProMAX® contains *f–k* migration, edge detection and seismic coherency (Marfut *et al.*, 1998) tools, all of which were used herein. Polarimetric GPR data acquisition processing (e.g. Sassen and Everett, 2009) and vector migration (Streich *et al.*, 2007) techniques, which take explicit account of the TX and RX orientations with respect to the buried objects and the vectorial nature of electromagnetic wave propagation, are gaining in use by the GPR research community but their application is beyond the scope of the present article and indeed beyond the reach of routine archaeological investigations. Such vector-wave processing methods go beyond what can be accomplished by a scalar wave propagation seismic

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package such as ProMAX®, and are mentioned here to illustrate improvements that should become widespread in the near future

Depth profiles along with time-slices and a historical knowledge of the site are essential for subsurface structure interpretation. The GPR technique was a useful tool for pinpointing the positions of potential twelfth century foundations at Valmagne, but difficulty in identifying GPR signatures indicates how problematic interpretation can be unless supported by actual excavations.

Although we were not able to confirm interpretations by excavating, based on the GPR results we believe that the twelfth century Romanesque building is likely to have had a rectangular termination flanked by chapels of unequal width opening off its transept in the manner of the abbey church of Fontfroide. We also believe the twelfth century Romanesque church to have been approximately the same length as the existing thirteenth century Gothic church. We were able to pinpoint and suggest identifications for several other subsurface objects, including possible Roman remains beneath the choir, tombs, choir screens, and rubble. Most important, our data serves to guide systematic archaeological survey and excavations. The results of this study are significant to medieval architectural history since they reveal new subsurface constraints on the nature of Cistercian construction in Languedoc.

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