

Mapping subsurface karst features with GPR: results and limitations

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Abstract Ground penetrating radar (GPR) has been applied, with relative success, to locate paleo-collapses and cavities and to detect and characterise karst. One of its main advantages is that, while the penetration depth is limited to several tens of meters or even just several meters, the obtained resolution can be in the scale of centimeters. In this paper, we illustrate the applicability of GPR prospecting to the study of alluvial karst and the structures associated with subsidence areas. GPR radar-grams obtained with two central frequency antennas (50 and 100 MHz) are balanced against direct observation of geological features of collapse structures in vertical exposures of gravel quarries. GPR-surveys offer the possibility of obtaining nearly continuous vertical cross-sections of the subsoil, and integration of data within a 3D frame. However, the study of the internal structure of the subsoil by means of the GPR-profiles has been usually neglected. In this work, we show that some hints about the evolution of individual dolines can be established from the study of the geometry of the sedimentary filling by means of GPR. The obtained results indicate that GPR allows to characterise the structures associated with karst features and can therefore be useful evaluating hazard susceptibility in doline fields, because: (1) when no surface evidences exists, it permits the detection of karst hazards in the subsoil, and (2) when surficial evidences of karst activity

are present, it permits the characterisation of processes associated with subsidence.

Keywords Karst subsidence · Doline · GPR · Ebro basin

Introduction

The study of doline hazards in the surroundings of Zaragoza has been an increasingly important research subject, related with the vulnerability of human structures. The main objective of these studies (Soriano 1990; Gutiérrez and Gutiérrez 1998; Soriano and Simón 1995; Benito et al. 2000; Soriano and Simón 2002; Guerrero et al. 2004; Soriano et al. 2004; Gutiérrez-Santolalla et al. 2005a, b and references therein) is to map hazard zones, to detect and to locate potential karst hazards and to study the evolution of these areas. The study of evolution of doline fields has been mainly based on the study of aerial photographs, measurements of subsidence activity, and the study of cross-sections of paleodolines.

In some cases, when outcrop observations are possible, the study of doline evolution can be focused in the study of the internal structure of the subsident areas, the absolute dating of deposits filling the cavities, and the progression of karst phenomena. In these situations, it is possible to have a cross-sectional view of the structure of alluvial deposits, but in most cases, it is difficult to obtain information about their 3D structure. Where outcrops are not present, the activity of the subsident zones can only be inferred from its effects at surface, with no information about the internal structure of the sub-soil.

The correct characterisation of the internal structure of karst hazard areas can give information about its vulnerability-susceptibility and the processes affecting the zone at

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present and in the recent past, and to propose evolutionary models based on the results of geophysical surveys. In this way, these data are additional tools to predict future processes associated with karst hazard zones.

Ground penetrating radar (GPR) has been widely used to characterise subsurface processes and structures. The application of GPR-surveys to karstic areas partially covered by alluvial deposits is not common, mainly because high clay contents of alluvial deposits are a handicap to the penetration depth of GPR-systems.

Studies carried out in karst zones have been mainly focused in the detection of cavities and paleo-collapses (e.g. Benson and Yuhr 1989; Collins et al. 1990, 1994; Doolittle and Collins 1998; McMechan et al. 1998; Chamberlain et al. 2000; Al-fares et al. 2002), and the study of the internal structure of the sediments has been frequently overlooked. The cited works prove that cavities and paleocollapses can be the origin of changes in the internal structure of the deposits, and, consequently, in the relative penetration depth, and reflectivity of em waves.

In this paper we show that, although in many cases it is not possible to reach the depths of origin of the karst hazard (i.e. cavities), the high resolution of GPR prospecting allows the sub-soil structure to be characterised and the presence of hazards in deeper locations to be inferred. We demonstrate that the contribution of GPR to evaluation of karst hazards goes beyond the mere detection of cavities and can help to unravel the evolution of karstic areas. Two different examples are analysed in the next sections, the first one represents the integrated study from geological observations at quarry cross-sections and GPR-surveys. In the second example, we explore the GPR applicability when cross-section exposures are not available and there is only partial surface information.

Methodology

Survey and processing

GPR is a non-destructive geophysical method that produces vertical cross-sectional images of the shallow subsurface, the resulting image (radargram) being very similar in style to seismic reflection profiles. GPR acquisition is based upon the propagation, reflection and scattering of high frequency electromagnetic waves (generally ranging from 10 to 1,000 MHz) within the subsurface.

Reflections are generated at boundaries between elements with contrasting electrical properties, depending on grain size distribution (sorting, clay content), porosity, water content and the electrical properties of the particles themselves (Knight and Nur 1987; Davis and Annan 1989; Annan et al. 1991). Consequently, subsurface features such as

sedimentary structures, lithological changes and the water table can all generate primary reflections (Neal et al. 2002).

Therefore, GPR results depend on the soil type and its state (saturation degree, compaction, etc.) but they also depend on the equipment used. In this work, we have used two different Ramac (Mala Geosciences, Sweden) GPR equipments: an unshielded bi-static antenna with central frequency of 50 MHz, and a shielded, bi-static antenna with central frequency of 100 MHz. The single measurements were triggered with time in the unshielded equipment, and with horizontal displacement in the shielded equipment. The correlation between both systems was helped with metric measurements and ticks in the profiles at regular horizontal intervals.

For the time-depth conversion along the vertical axis (two-way time in ns) a constant propagation velocity was estimated from the modelling of subsurface scattering diffractions appearing on the raw data (fitting hyperbolae) in each survey. Velocities estimated from hyperbola fitting are between 60 and 80 mm/ns, representative for agricultural soil (Reynolds 1997). The horizontal discrimination resolution by means of the First Fresnel Zone gives values between 1.7 and 1.9 m (Reynolds 1997) for a 1-m deep target. These values are a mathematical approximation, and in the case of the First Fresnel Zone, they represent the distance at which two different objects with similar electromagnetic properties could be distinguished, the identification resolution being lower than this distance, although it also depends on the depth and dielectric constant of the target.

Profile processing included sequential zero-time corrections, running average filter, exponential gain function, band-pass filter and plotting. Correct profile processing is necessary to characterise the structure of the subsoil, and the previous routine has demonstrated an acceptable success. Topographic corrections were only applied in some profiles because terrain slopes were usually shallower than 5°. Topographic correction should be considered in regions with surface gradients >10%, and slope angles >6° (Lehman and Green 2000). The stacking processing was only applied in profiles where vegetation growth did not allow for a stable displacement.

In all the surveys, cleaning of metallic elements in the survey zone was done before the survey, to avoid the influence of high reflectivity elements at surface. During the survey, the ground signal was identified by changing the position of the antennas with respect to the floor (methodology described in Annan 2003). In the case of the unshielded 50 MHz equipment, the possible influence of the lateral, excavated walls of the quarry in the surroundings of the prospecting area was minimised by defining the survey grid parallel to the walls. In this way, cross anomalies in the radargrams are reduced to a minimum.

Grid maps

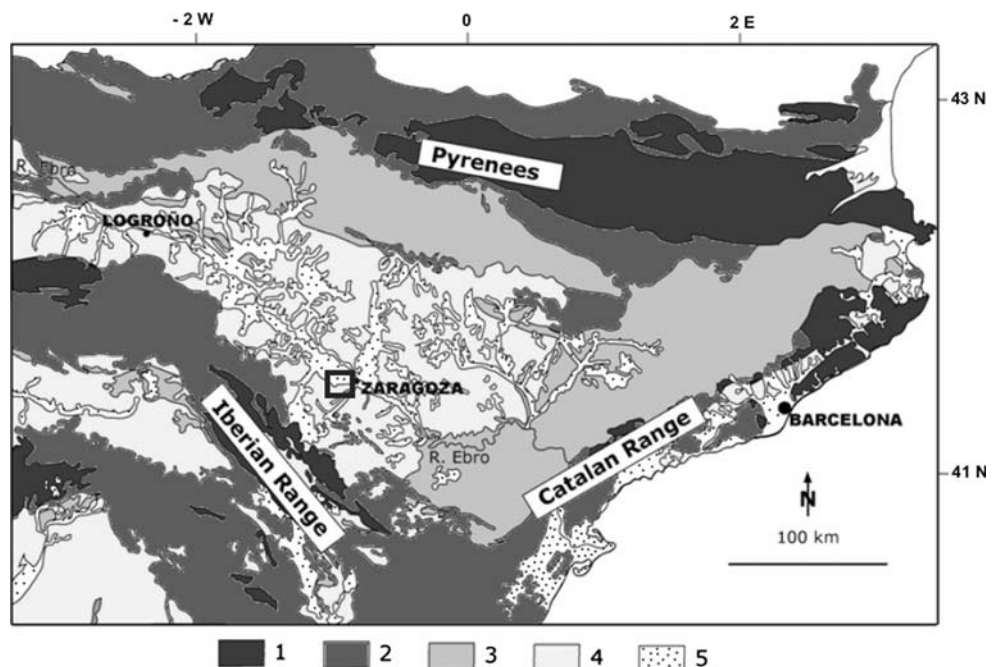
If we assume that the sub-soil is EM homogeneous, the penetration depth of EM waves is related to the wave emission and the electromagnetic properties and state of the materials. In cases where lithology changes laterally, the penetration depth can be used to identify the prospected materials. In these cases, there is also an abrupt change in the wave propagation properties that can be identified from the raw data by a hyperbolic anomaly or an EM anomalous behaviour zone. In the raw data, echoes of these anomalies generate changes in the apparent penetration depth that can also be used as indicators of anomalous zones in the profiles. If several parallel profiles are available, maps showing these changes can be drawn, allowing the correlation of anomalous sectors to be defined in 2D. The real penetration depth is usually difficult to establish, because of the difficulty in identifying if either the wave is attenuated or the behaviour of the material is homogeneous. The qualitative or relative penetration depth can be established by comparing the wavelength at different depth intervals and by correlating parallel profiles, or different sectors of the same profile. These results can be used to estimate the reflectivity (related to amplitude) and the intensity of the wave. All these data allow for an estimate of the penetration depth and the intensity of the wavelength that indicates the wave decay at this depth, provided that the material is homogeneous. Qualitative changes in wave propagation are usually observed as reflections in single radargrams or as positive anomalies in the grid maps (qualitative indicator of higher reflectivity and higher penetration depth). Zones

with higher wave attenuation are observed as blank zones in the profiles or negative anomalies in residual grid maps (since there is no real penetration).

Geological framework of the Zaragoza area: karstic processes

The presented examples come from surveys across the central part of the Ebro Basin (Fig. 1). The Tertiary Ebro Basin (NE Spain) is bounded by the Pyrenees, the Iberian Range and the Catalan Coastal Range. The evolution of the basin during the Cenozoic was mainly controlled by the development of the Pyrenean Range. During the Late Eocene the connection with the Atlantic Ocean was closed and in the central sector of the Ebro Basin the Oligocene-Miocene series were deposited in alluvial fan, evaporitic and carbonate lacustrine systems (Pardo et al. 2004) that generated detrital, evaporite, and carbonate rocks (Fig. 1). During the Neogene (12–8.5 Ma) this evaporitic basin opened to the Mediterranean Sea (Pérez-Rivarés et al. 2002; García-Castellanos et al. 2003), thus changing its base level with subsequent dominating erosion processes and short sedimentation episodes. Accordingly with the end of the main period of tectonic activity about the Oligocene–Miocene boundary, the Neogene rocks show near horizontal bedding with very gentle folds (Arlegui and Simón 2001). The Quaternary deposits of the central zone of the Ebro basin consist of alluvial and fluvial units, mainly related with the Ebro river and its tributaries, and partially covering the Tertiary rocks.

Fig. 1 Geological map of Northeastern Spain with the location of the Ebro basin and the studied area (1: Paleozoic, 2: Mesozoic, 3: Paleogene, 4: Neogene, 5: Quaternary)



Karst processes in the surroundings of Zaragoza are related to the solution of Miocene evaporitic rocks partially overlain by Quaternary materials. The thickness of Quaternary deposits is not uniform: while in some sectors they are only represented by an edaphogenic cover less than 0.50 m thick, in other sectors near the Ebro river they are several tens of meters thick. Karst activity is witnessed by structures in most of the Quaternary fluvial levels, and is still active at present in the lower terraces and the alluvial plane.

The result of solution processes is the formation of cavities, subsidence, and the collapse of these cavities. The different surface morphologies resulting from karstic processes are mainly related to the cohesive behaviour of the Quaternary materials (Soriano and Simón 1995). Cavities develop in the subsoil in areas where a cap-rock permits to isolate the evolution of the solution zone from the uppermost materials. These cap-rocks can be Miocene limestones, gypsum levels or edaphogenic carbonate crusts within the Quaternary deposits. The presence of a cap-rock and its rheological properties control karst features in subsurface conditions: when the cap-rock is strongly cohesive, the presence of an active karst hazard can only be observed after the collapse. The other end-member occurs when there is no cohesive level and continuous subsidence is the dominant process during progressive solution of the gypsum underneath. Intermediate cases occur when a thick alluvial level is present, the cavity has no surface indicator and deposits accommodate into a deep cavity (alluvial dolines).

Case study 1: comparison with outcrop observation

The first example is a detailed study in a gravel quarry. The vertical exposure (more than 300 m long and 12 m high) shows a paleo-collapse affecting alluvial deposits (Fig. 2) consisting of gravels, sands and clays. Bedding is nearly horizontal, except for dipping cross-bedding laminae in the uppermost gravel deposits and the central part of the exposure, where a clay-rich zone, separated from the gravels by sharp limits, can be observed. In this clay-rich zone, changes in dip define a syn-sedimentary syncline. Beds defining the limbs of the syncline are cut by normal faults in the lower part of the section, whereas in its upper part there is lateral continuity of the sedimentary units, that become thicker towards the central part of the section (i.e. over the collapse).

Two GPR-surveys (50 and 100 MHz) were done in this quarry. The survey grids were established parallel to the quarry walls to minimise aerial or cross anomalies. Differences between the two surveys are mainly referred to the reached depth, consistently with the central frequency of the equipments.

The 100 MHz survey shows an overall syncline geometry (Fig. 2), where the more depressed zone can be directly related to the collapsed area. The upper part of the profiles shows an overall horizontal geometry, whereas in the deeper zones, reflectors with dips increasing towards the central part of the profile can be observed. Some reflectors are discontinuous. In these zones most of the

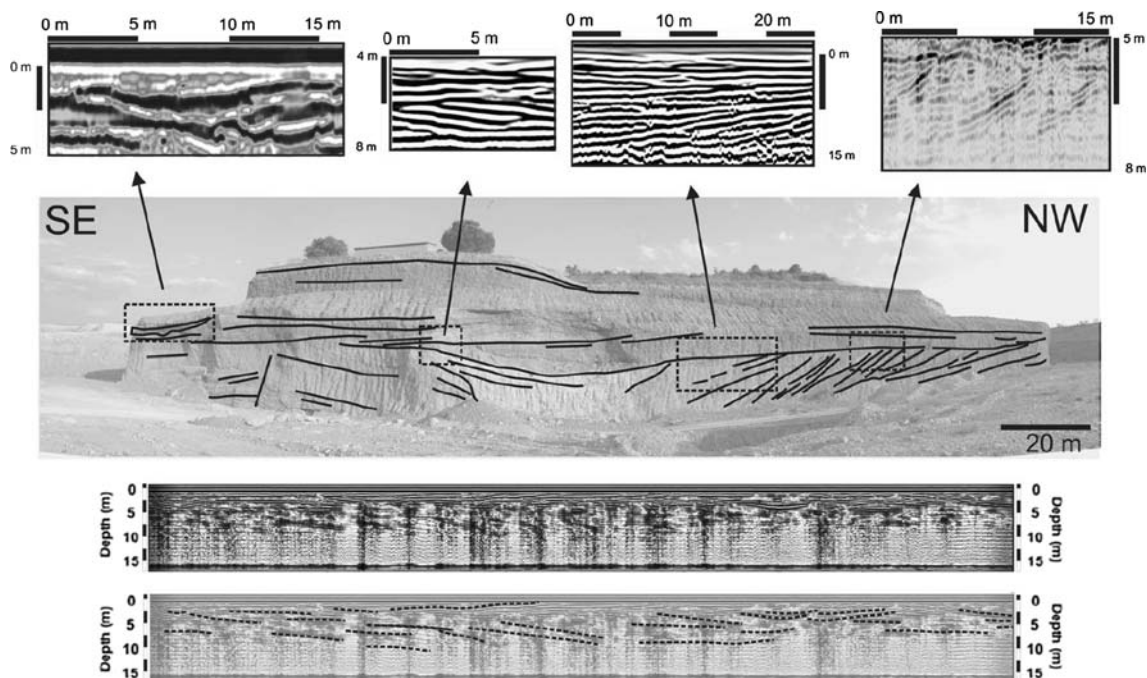


Fig. 2 Outcrop photography of the prospected quarry with several profile section examples and one of the complete profiles surveyed with the 100 MHz central frequency antenna (scale bar in meters)

changes in dip of the reflectors can be observed, some of them related to faults cropping out at the quarry exposure. In the GPR-profiles it is not possible to define clearly the collapsed zone, because of the shallow penetration depth, but it is possible to identify the subsident area related to folded reflectors directly located over the collapsed zone.

The 50 MHz survey shows similar results (Fig. 3). The central syncline and the on-lap geometries at the margins of the subsident area can be clearly observed. The lateral limits of the depleted zone do not show clear reflectors, but dip changes of the reflectors can be used as indicators for the boundary faults of the collapsed zone.

Considering the geometry of the reflectors and the different behaviour of waves in the profiles, several zones can be defined (Fig. 4): (1) A zone characterised by a homogeneous behaviour of the waves and/or parallel reflectors. No lateral changes of the wavelength are observed and it is possible to infer a parallel disposition of the changes of polarity of the wave (amplitude sign). This zone represents the direct wave and the homogeneous zone of the upper zone of the subsoil. After applying background filtering this parallel disposition of reflectors remain in some of the profiles. Furthermore, outcrop observations show a parallel disposition of layers in this zone. (2) A zone delimited by on-lap reflector geometries appearing in the marginal zone of the studied profiles (in profiles crossing the zone with indicators of karst activity). The limits between this unit and the others have been defined by means of the lateral correlation of the adaptation features. In this way, it is

possible to correlate different accommodation features in the marginal zone of the profiles. (3) A zone without signal in the raw data, with homogeneous behaviour or with parallel, horizontal disposition of the reflectors and with no lateral correlation with the reflectors observed out of this zone. (4) A zone with folded reflectors or where there is no lateral continuity of the reflectors. Furthermore, the upper part of the profiles shows homogeneous behaviour or parallel horizontal reflectors (in some cases this zone represents just the change of the amplitude sign of the wave) that can be related to the homogeneous structure of the subsoil and the direct wave propagation. The on-lap reflector geometries are located in the central part of the profiles, where their lateral continuity increases at shallower depth. Below these zones the waves are strongly attenuated.

A close similarity is observed when comparing the results obtained from the radargrams and the outcrop (Fig. 4). This correspondence extends to the processes that can be inferred from their geometry. Observations evidence a zone with no subsidence features (parallel bedding, zone 1), a zone with folded beds that lose their lateral continuity against faults (zone 4), and zones showing an overall syncline geometry that show growth strata (zone 2) or folded levels with uniform thickness (zone 3). These features allow to infer pre-karst sedimentation for zones 3 and 4, syn-karst sedimentation in zone 2 and probable post-karst sedimentation for the upper unit (zone 1), provided that it is not a cap-rock for the collapse. This relative

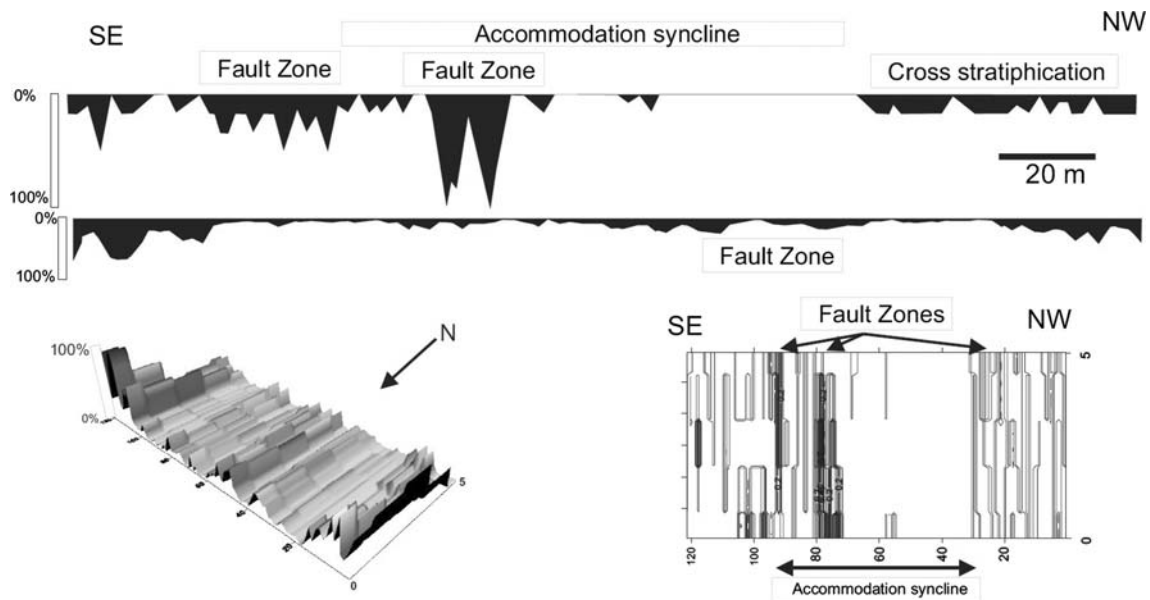


Fig. 3 a Cross-section of the qualitative penetration depth of the surveyed profiles. b 3D view of the results obtained by lateral profile correlation in the surveyed quarry (qualitative wavelength lateral correlation). c Map view of the prospecting grid with the echoes,

some of them correlated with fault-zones. The lack of data in the central part of the figure is related to clay-rich deposits in the core of the accommodation syncline (scale bars in meters)

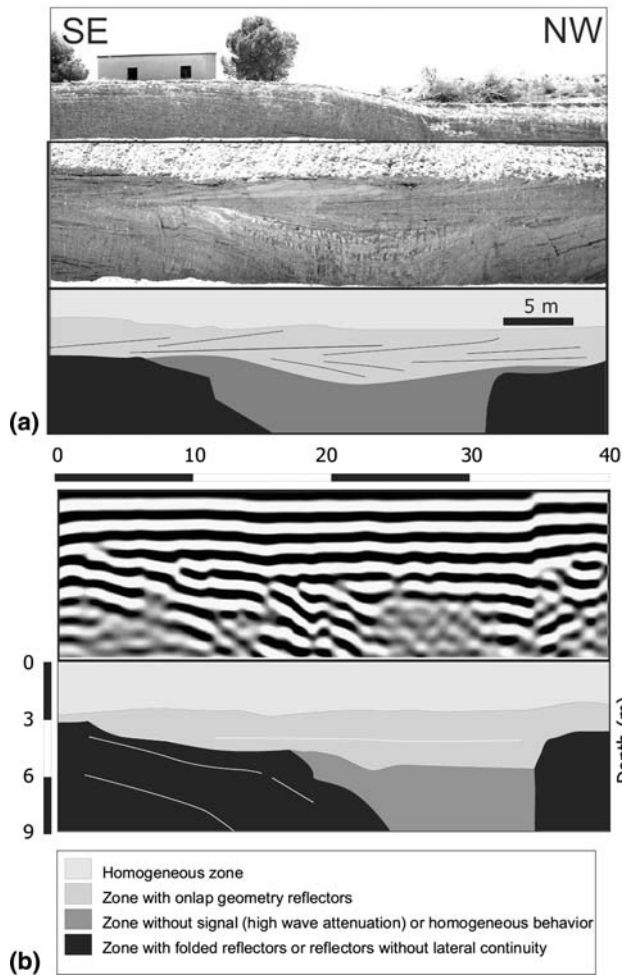


Fig. 4 **a** Detailed photograph of the collapsed zone, where the zone classification has been applied. **b** Radargram where the classification used in **a** has been applied (*scale bar in meters*)

chronology and processes obtained from the study of the quarry exposure can be extrapolated to the radargrams.

Case study 2: a doline field

The results obtained from the comparative study between the quarry section and the GPR-profiles show the possibility for this methodology to be applied to places where direct observation of exposures is not possible. We applied GPR-survey in a doline field, where recent evidences of subsidence activity were obtained from interviews to local farmers. The doline field is located in a farm area, part of it wild waste land because of the presence of collapses at surface (Fig. 5). The preliminary field study showed shallow cavities. The GPR-survey was done with a 50 MHz system, following a square grid along two orthogonal directions. The processing routine and zone classification applied to the former example have been also used here.

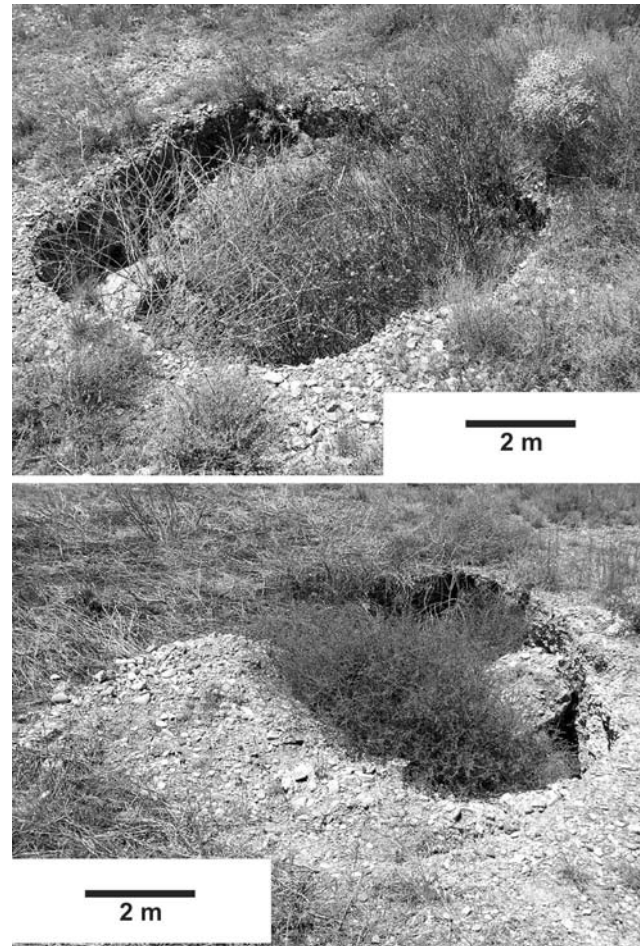


Fig. 5 Field photographs where collapses affecting the surface can be observed (*scale in the figure is in meters*)

In this doline field it was possible to establish different evolutionary stages for a specific karstic process: (1) collapsed zones where the presence of a more cohesive surficial level has allowed to generate an underground cavity and a subsequent collapse, (2) subsident zones, detected at surface by differential vegetation growth patterns, and (3) sites where no surficial evidences have been reported but where sub-surface cavities can be interpreted from the geophysical survey. In many cases surficial evidences were identified in the field after the GPR-survey, which was therefore used as a guide to identify collapse areas.

In the first approximation the surface cavities where mapped, and after the GPR-survey interpretation, a direct comparison between the GPR results and the surface evidences was done. From the two data sources it was possible to establish that, in some cases, differential growth vegetation patterns can be correlated with zones of continuous subsidence determined by means of the GPR-profiles and the grid maps. Maps of relative variation of penetration

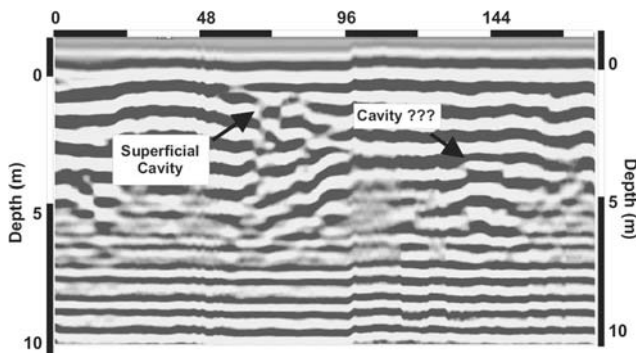


Fig. 6 Radargram of the doline field surveyed with the 50 MHz GPR equipment where a superficial cavity has been pointed out from the GPR results. In the right part of this radargram an anomalous sector of wave behaviour has been pointed out. This second zone can represent a cavity in the sub-soil (*scale in the figure is in meters*)

depth show three aligned negative anomaly zones (Fig. 7), coinciding with areas of relatively shallower penetration depths of the GPR-survey. One of them is near a collapsed area, and the others only show evidences of differential pattern of bush growth. The central anomaly shows a zone (zone 1) extending from the surface to three meters depth, characterised by homogeneous behaviour of the waves or parallel horizontal reflectors. Below this zone, an upper part with on-lap reflector geometries that extended across zones 3 and 4 can be observed. From relative chronology criteria, we can infer pre-karst sedimentation in zone 4 and syn-karst sedimentation in zones 2 and 3 (Fig. 8). The homogeneous zone, which can be partially related to the direct wave, also represents a zone not affected by karst activity. In other places of this doline field, it was possible to identify important variations of the propagation properties of EM waves that show the features usually related with the presence of cavities in the subsoil (Figs. 6, 7).

Discussion and conclusions

The study of a gravel quarry section by means of direct observations of paleo-karst activity has allowed the evolution of a collapsed doline to be reconstructed. The parallel study of this section with the GPR-survey allows for a direct correlation between the described zones in the profiles and in the quarry section to be established. This direct correlation shows that the same processes inferred from the geometry of the Quaternary beds, can be inferred in the radargrams by the study of the geometrical relations of the reflectors. This simple methodology allows to define a relative chronology of pre-, syn-, and post-karst sedimentation, both in the cross-section and in the GPR-profiles.

The application of this methodology to a doline field, with the study of qualitative penetration depth variations

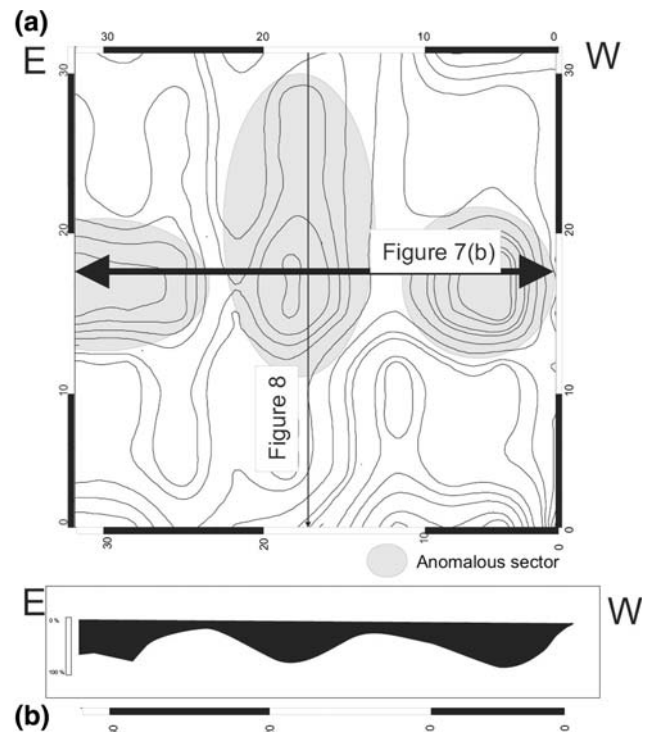


Fig. 7 **a** Grid map of the surveyed field where zones of anomalous sectors of penetrativity have been defined. **b** Cross-section of the penetrativity variation established by means of the wavelength in residual depth conditions (*scale bar in meters*)

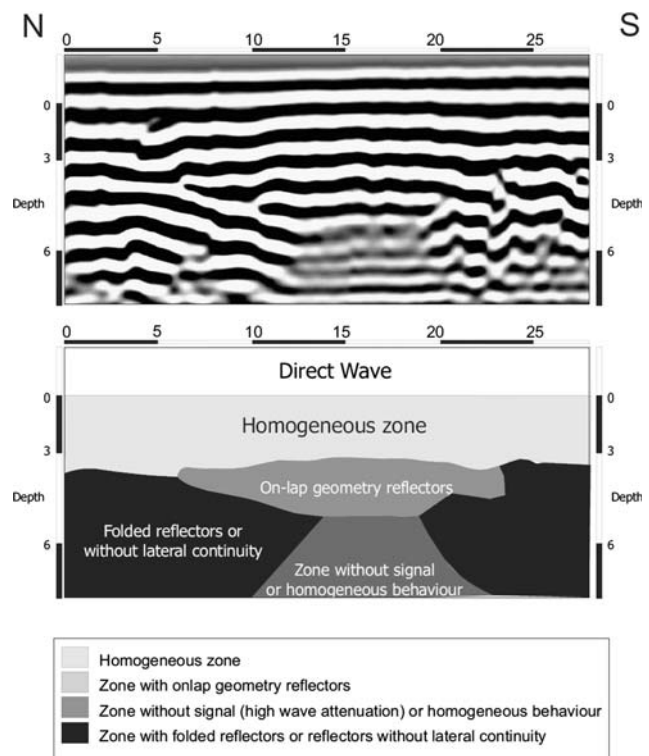


Fig. 8 GPR-profile where the zone classification has been applied (see location in Fig. 7, *scale bar in meters*)

and the geometrical classification of zones offers the possibility of inferring processes and in some cases of establishing their relative chronology in a zone where direct observation is not possible. The definition of the relative chronology relationships allows to evaluate the vulnerability of the studied zones and therefore, to apply GPR-surveys to characterise karst hazards.

The studied examples show different states of doline evolution around the Zaragoza area. In these cases, as it occurs in many doline fields, the analyses are circumscribed to the consequences of evaporite solution in the overlying Quaternary alluvial deposits. The origin of the karst hazards is related to the solution of evaporites in the Miocene bedrock but the direct observation of the process is difficult and in many cases impossible. The study of man-made and natural cross-sections in quarries are also restricted to the results of the solution processes in the upper levels (accommodation, subsidence, collapses, etc.), but, except for outstanding sites, does not allow to study the causative cavities in the Miocene evaporites. GPR-surveys do not solve this problem, but give detailed information about the consequences of the solution processes in the alluvial deposits.

The methodology proposed in this work can be of significant help in studies where direct measurements over subsident zones are undertaken, maps from aerial photographs are defined or where a section to study the structure of karst zones is needed. GPR-surveys can contribute to characterise shallow karstic evidences and help in the location of anomalous zones related to different behaviour in the propagation of EM waves or different penetration depths and sometimes where no surficial evidences exists. In the case of the presence of a collapse the interpretation of GPR-profiles is usually straightforward, but when relative chronological relationships are to be established, more assumptions are needed during interpretation. When on-lap reflector geometries are present in the profiles and show a closed encircle in map view with a higher clay content, it is possible to interpret a subsident zone from the geometrical features in the profiles and thickness variations in the filling of the subsident zone. Zones with higher clay content show higher attenuation of EM waves, and therefore they can be identified by their apparent lower penetration depth in the raw data. This is associated with a particular internal structure of the subsoil with accommodation features (syndimentary syncline) and on-lap reflector geometries.

When characterising the activity of the subsident zones, as in the first example presented in this work, the presence of a homogenous zone without reflectors or parallel reflector geometry gives the post-karst chronology to the upper part of the sequence. In the second example, the homogeneous zone represents the non-affected cap-rock overlying the collapsed zone. Where a cap-rock exists, a

cavity can develop without evidences at surface (a) if partial collapses do not reach the surface, and (b) if internal re-organisation of the deposits takes place within the cavity (for example progressive sedimentation of particles from the roof over the lower zone of the cavity). In these cases, the presence of an upper homogeneous zone, without internal structure or with parallel reflector disposition, does not indicate post-karst sedimentation. It just means that the cavity has not reached the surface and that the surficial collapse has not happened yet, or that the cavity has been filled with material from a lateral zone of the prospected area. In these cases, obtained results are difficult to correlate directly with the chronological sequence of the processes. In the presence of cavities and paleocollapses, when subsidence affects the topographic surface, the timing of collapse can be related to the sedimentation of surface deposits, which can be subsequently affected by subsidence. In cases where there is a cap-rock that individualise the lower materials from the upper, the exact chronology can be difficult to establish and it is only possible to define whether they are affected by karst activity or not. However, the presence of a cavity identified in the profiles represents an imminent karst hazard.

The main applicability of GPR-surveys in engineering geology comes from its straightforward use to locate anomalous zones in the subsoil, and to identify the geometrical features of these anomalous zones. This methodology shows that grid maps and the structural classification can be used to delimit the areas suitable for boreholes or other geophysical surveys. In some cases it is possible to establish the relative chronology of the processes and in others just to show the presence of changes of the EM behaviour of the waves in the subsoil that can be related with the variation of other physical properties (porosity, density, saturation, etc.). In the case of investigation of karst hazards at regional scale, where the usual study techniques are aerial photographs, mapping and farmer interviews, GPR-surveys can represent a useful tool to increase the information and knowledge of hazard zones, or to locate zones that do not show surface evidences. The different signals obtained in collapsed zones, cavities and subsident zones allow to establish a qualitative evaluation of the karst hazard improving the knowledge about mapped hazard zones and to locate other areas without surficial evidences of activity. The relative chronology established by means of the structural classification of the GPR-profiles can be very useful and straightforward in some cases, and in others it can be just useful to delimit the origin, activity and potential karst hazard in places without the availability of good exposures. This information can be used to evaluate the potential karst hazard in these zones.

The absence of activity over the hazard zones can be established in some cases by means of non-deformed beds.

In other cases, the upward propagation of collapses implies that the uppermost materials are not affected by the collapsing process, even when the process can still be active. In these cases, photogeological studies and farmer interviews can be a very important way to obtain information about the chronology of the activity, while GPR is useful to characterise the detailed structure of each sedimentary unit in every individual collapse and to locate and characterise karst hazards with or without surficial evidences of karst activity (continuous subsidence, cavities and/or paleo-collapses).

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References

- Al-fares W, Bakalowicz M, Guérin R, Dukhan M (2002) Analysis of the karst aquifer structure of the Lamalou area (Hérault, France) with ground penetrating radar. *J Appl Geophys* 51:97–106
- Annan AP (2003) Ground penetrating radar: principles, procedures & applications. Sensors & Software Inc, Mississauga, p 271
- Annan AP, Cosway SW, Redman JD (1991) Water table detection with ground-penetrating radar. *Soc Explor Geophys* 494–497 (Annual International Meeting Program with Abstracts)
- Arlegui LE, Simón JL (2001) Geometry and distribution of regional joint sets in a nonhomogeneous stress field: case study in the Ebro basin (Spain). *J Struct Geol* 23:297–313
- Benito G, Gutiérrez F, Pérez-González A, Machado MJ (2000) Geomorphological and sedimentological features in quaternary fluvial systems affected by solution-induced subsidence (Ebro Basin, NE-Spain). *Geomorphology* 33:209–224
- Benson RC, Yuhr LB (1989) Assessment and long term monitoring of localised subsidence using ground penetrating radar. *Int J Rock Mech Min Sci Geomech Abstr* 26(5):246 Proc 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, Orlando, 9–11 February 1987. Balkema, Rotterdam, pp 161–169
- Chamberlain AT, Sellers W, Proctor C, Coard R (2000) Cave Detection in Limestone using Ground Penetrating Radar. *J Archaeol Sci* 27:957–964
- Collins ME, Puckett WE, Schellentrager GW, Yust NA (1990) Using GPR for micro-analyses of soils and karst features on the Chiefland Limestone Plain in Florida. *Geoderma* 47:159–170
- Collins ME, Cum M, Hanninen P (1994) Using ground-penetrating radar to investigate a subsurface karst landscape in north-central Florida. *Geoderma* 61:1–15
- Davis JL, Annan AP (1989) Ground penetrating radar for high resolution mapping of soil and rock stratigraphy. *Geophys Prospect* 37:531–551
- Doolittle JA, Collins ME (1998) A comparison of EM induction and GPR methods in areas of karst. *Geoderma* 85:83–102
- García-Castellanos D, Vergés J, Gaspar-Escribano JM, Cloething S (2003) Interplay between tectonics, climate and fluvial transport during the Cenozoic evolution of the Ebro Basin (NE Iberia). *J Geophys Res* 108(B7):2347
- Guerrero J, Gutiérrez F, Lucha P (2004) Paleosubsidence and active subsidence due to evaporite dissolution in the Zaragoza area (Huerva River valley, NE Spain): processes, spatial distribution and protection measures for transport routes. *Eng Geol* 72:309–329
- Gutiérrez-Elorza M, Gutiérrez-Santolalla F (1998) Geomorphology of the Tertiary gypsum formations in the Ebro Depression (Spain). *Geoderma* 87:1–29
- Gutiérrez-Santolalla F, Gutiérrez-Elorza M, Marín C, Desir G, Maldonado C (2005a) Spatial distribution, morphometry and activity of La Puebla de Alfindén sinkhole field in the Ebro river valley (NE Spain): applied aspects for hazard zonation. *Env Geol* 48(3):360–369
- Gutiérrez-Santolalla F, Gutiérrez-Elorza M, Marín C, Maldonado C, Younger PL (2005b) Subsidence hazard avoidance based on geomorphological mapping in the Ebro River valley mantled evaporite karst terrain (NE Spain). *Env Geol* 48(3):370–383
- Knight RJ, Nur A (1987) The dielectric constant of sandstones, 60 KHz to 4 Mhz. *Geophysics* 52:644–654
- Lehmann F, Green AG (2000) Topographic migration of georadar data: Implications for acquisition and processing. *Geophysics* 65(3):836–848
- McMechan GA, Loucks RG, Xiaoxian Zeng, Mescher P (1998) Ground penetrating radar imaging of a collapsed paleocave system in the Ellenburger dolomite, central Texas. *J Appl Geophys* 39:1–10
- Neal A, Pontee NI, Pye K, Richards J (2002) Internal structure of mixed-sand-and-gravel beach deposits revealed using ground-penetrating radar. *Sedimentology* 49:789–804
- Pardo G, Arenas C, González A, Luzón A, Pérez A, Pérez-Rivarés FJ, Vázquez-Urbez M, Villena J (2004) La cuenca del Ebro. In: Vera JA (ed) *Geología de España*. SGE-IGME, pp 533–543
- Pérez Rivarés FJ, Garcés M, Arenas R, Pardo G (2002) Magnetocronología de la sucesión miocena de la Sierra de Alcubierre (sector central de la Cuenca del Ebro). *Rev Soc Geol Esp* 15(3–4):217–231
- Reynolds JM (1997) An introduction to applied and environmental geophysics. Wiley, Chichester
- Soriano MA (1990) Geomorfología del sector centro-meridional de la Depresión del Ebro. Diputación Provincial de Zaragoza, p 269
- Soriano MA, Simón JL (1995) Alluvial dolines in the central Ebro Basin, Spain: a spatial and developmental hazard analysis. *Geomorphology* 11:295–309
- Soriano MA, Simón JL (2002) Subsidence rates and urban damages in alluvial dolines of the central Ebro Basin (NE Spain). *Env Geol* 42(5):476–484
- Soriano MA, Simón JL, Arlegui LE, Liesa CL, Pocoví A (2004). Problemas causados por el karst aluvial en el centro de la cuenca del Ebro (España). In: *Proceedings of the Workshop Stato Dell'arte sullo studio dei fenomeni di sinkholes e ruolo delle amministrazioni statali e locali nel governo del territorio*, APAT, Rome, pp 521–532