Fire effects on soil properties and spectral behaviour

Ascertaining the effects of fire on the soil is crucial for application of remedial measures. The trouble is, however, that current fire-severity estimation methods are usually costly, subjective and imprecise. The Fire Research Centre (Centro de Investigación del Fuego: CIFU) has assessed the potential of VNIR radiometry for rapid and efficient determination of the effects on soil properties of fires of varying duration and intensity...

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Accurate estimation of soil changes after a forest fire is a sine qua non of efficient restoration measures afterwards. Post-fire management and palliative treatment (reforestation, logging, erosion protection, priority action maps, etc) are not always the same; their particular character in each case depends on the fire severity and post-fire soil effects. Furthermore, fire severity and concomitant effects are often patchily distributed. It is therefore also important to find out the spatial distribution of fire severity over the whole affected area.

Despite the importance of assessing fire effects on the soil, the current fire-severity estimation methods are usually costly, subjective and imprecise (1). Prompted by the need to fill this methodological gap, the Fire Research Centre (Centro de Investigación del Fuego: CIFU) has conducted a study to weigh up the potential of VNIR radiometry for rapid and efficient determination of a fire’s effect on soil properties. To this end a study has been made of which heat shock treatments are important for assessing the effects of real fires and how to put such treatment into practice in a methodologically robust manner (i.e. ensuring that measurements are comparable in each case). The study involved a combination of traditional techniques for ascertaining the fire effect on soil (by means of laboratory physicochemical analysis) and the most recent VNIR radiometry methods (using an ASD FieldSpec 3 spectroradiometer). This 12-month, FUNDACIÓN MAPFRE-financed research project analysed and ascertained the fire effect on soils and also the precision of VNIR radiometry in detecting and identifying these effects.

VNIR radiometry

Radiometry in general is a set of scientific techniques for measuring electromagnetic radiation. VNIR radiometry in particular measures electromagnetic radiation in the visible (VIS) and near infrared (NIR) ranges of the spectrum (350 to 750 nm and 750 to 2500 nm respectively). These spectrum regions take in the wavelengths in which soil components show a distinctive spectral behaviour, allowing for their identification and quantification (2). This technique represents a rapid and precise alternative for assessing soil property changes after a forest fire.

VNIR radiometry offers several advantages over other analytical techniques. First and foremost it is a very quick analysis (<
This study represents the start of a line of research of great interest for the restoration of burnt areas, such as the use of remote-sensing techniques for studying the severity of forest fires. Conversely, there are many factors impinging on the spectral and spatial variability of a soil sample, so it is no easy matter to establish a cast-iron relationship between the soil properties and spectral curves. There was therefore little takeup of radiometry as an analytical technique until computers’ calculation capacity became powerful enough to deal with it. Each VNIR radiometry spectrum is made up by hundreds or thousands of data and calls for relatively complex calibrations for its analysis. Until recently this analysis was unaffordable or technically impractical.

**Fire Severity**

When speaking about fire effects it is important to distinguish between fire intensity and fire severity, which are often not the same thing at all. The term intensity is used to describe the speed at which the fire releases heat energy. It is usually quantified in terms of fireline intensity, since this variable is bound up with flame length and is therefore easily measurable. Fire severity, for its part, is a more qualitative concept, referring to the fire’s effect on ecosystems. High-intensity fires might therefore lead to significant soil changes, in which case they would be classed as high-severity fires. This is not always the case, however. Latent, low-intensity fires, for example, can turn out to be of high severity if they bring about significant changes in the heated soil or even nearby soil. In this case the decisive fire-severity factor would not be so much its intensity but rather the temperature exposure time. Finding out fire severity is therefore crucial for describing the fire’s effects on the ecosystem’s soil.

**Study Methodology**

The study methodology is summed up in figure 1. First of all two types of soil with sharply contrasting edaphic properties were selected and sampled. Soil 1, taken from a Spanish Fir (Abies pinsapo) wood in Parque Natural Sierra de las Nieves (Málaga), is limestone soil with a high content of organic matter. Soil 2, in contrast, taken from Cistus (rockrose) and heather scrub in the hunting grounds of Quintos de Mora (Toledo), is siliceous soil with a low organic matter content.
VNIR-radiometry determination of the properties of burnt soil

Figure 1. Working methodology for the project «VNIR-radiometry determination of the properties of burnt soil».

Table 1. Conditions (temperature and exposure time) of the heat shock treatments to which the soil samples were subjected (Tmnt. = Treatment; T = Temperature in °C).

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All the treated samples (plus the control samples) were then analysed. Traditional laboratory analyses were conducted alongside VNIR radiometry analysis. Given the importance of soil fertility for post-fire regeneration of the vegetation, the traditional physicochemical analyses centred on those variables that are typically bound up with soil fertility. The following variables were hence assessed: organic matter content, total nitrogen, available inorganic phosphorous, cation exchange capacity, exchangeable Ca, Mg, Na and K content, pH, texture and total carbonates. The laboratory analyses allowed us to assess and determine the soil effects as a result of the test processes and also to study the relationship between these effects and the VNIR radiometry results.

The spectral analysis, using an ASD FieldSpec 3 radiometer (Analytical Spectral Devices Inc., Boulder, CO, USA), was conducted on the same samples used for the traditional laboratory analysis. A measurement protocol was designed for the radiometric readings. This protocol involved preparing the samples for measurement, fitting out the measuring room (minimising problems of diffuse reflectivity), the spatial layout of the lighting sources in relation to the sensor and sample (figure 3) and the configuration of the radiometric readings properly speaking. These readings allowed us to assess the heat shock effect on the soil’s spectral behaviour.
Precise calculation of post-fire soil changes is a sine qua non for efficient programming of subsequent restoration tasks.

Results

Heat shock treatment produced colour changes appreciable to the naked eye (figure 4). These colour differences show the fire’s effect on the soil’s spectral behaviour, affecting at least the visible zone of the spectrum (up to 750 nm). Radiometry was then used to evaluate quantitatively the changes in the spectral behaviour of the treated soils, and also to assess changes in the NIR region (not visible to the naked eye).

The spectral response of the studied soil (without heat shock treatment) is shown in figure 5. The radiometric measurement spectra comprised 2150 individual reflectivity readings. For the statistic analyses a selection was made of 11 wavelengths representative of the complete spectra (selected wavelengths are shown in figure 5). Wavelengths were selected on the following criteria: a visual analysis of the spectra obtained, the statistical analyses themselves and the position of the spectral bands present in the TM sensor of the Landsat satellite.

The spectra obtained from the samples treated with heat shock (figure 6) show a decline of reflectivity values throughout all spectrum regions analysed, as well as lower water absorption peaks (for wavelengths of 1400, 1900 and 2200 nm).

Figure 4. Aspect of the soil 2 samples after heat shock treatment. Rows and columns show, respectively, treatment of the same time and exposure temperature. The control sample is shown to the right.

Figure 5. VNIR spectra of the untreated soil samples (control samples) and location of the wavelengths selected for the statistical analysis.
Both processes occur gradually as temperature and exposure-times increase. Thus, water absorption peaks fall away completely at the highest temperature and exposure times. Changes in the spectral behaviour associated with the presence of water in the sample occur mainly in the NIR region (in the water absorption peaks); as such they are not visible to the naked eye. As for the fall in reflectivity values, this trend is inverted for treatments of greater severity (i.e., longer time and higher exposure temperature). In the treatments of greatest severity, reflectivity values increase, especially in the spectrum region corresponding to red and NIR. This behaviour shows the same general pattern for all soils studied. According to the statistical analyses carried out on the 11 selected wavelengths, the differences found in reflectivity values were statistically significant ($p<0.01$). VNIR radiometry is therefore a very sensitive technique for detecting post-fire soil changes.

The laboratory-conducted physicochemical analyses, for their part, showed up a decline in the content of organic matter, in the cation exchange capacity and clay percentage. These changes were not significant in general for the least severe treatments (for example treatment at 200°C or less than 1 minute). The laboratory physicochemical analyses also detected a significant increase (although in general only for treatment at more than 200°C and 1 minute) in pH, assimilable phosphorous content and exchangeable forms of Ca. As for exchangeable K, there was an initial fall in the concentration of this exchange base (for treatment of intermediate severity), but this trend inverted at 5 minutes duration for treatment at 700 °C and at 10 minutes for treatment at 600 °C. No significant differences were detected or a clear pattern in the behaviour of total nitrogen concentration or exchangeable forms of Na and Mg. Table 2 sums up the general trends observed in this group of variables in terms of the increase of exposure time or temperature reached during the treatment.

<table>
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<tr>
<th>Temperature increase From 200 to 700°C</th>
<th>Increase in exposure time From 1 to 30 min.</th>
<th>Temperature x time interaction</th>
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Figure 6. Spectral response of soil 2 samples after heat shock treatment.
The use of remote-sensing techniques would offer, among other advantages, the chance of finding out and studying the spatial distribution of fire severity throughout a whole territory.

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*CIC =
D+ = There are significant differences and most increase. D- = There are significant differences and most decrease. IG = There is no clear behaviour pattern and no clear differences. IN = There is interaction between factors of temperature and time. NO = There are no significant differences.

**Conclusions and proposal of future lines of research**

These study results demonstrate the usefulness of VNIR radiometry for calculating the effects of forest fires on soils. A solid methodological base has also been laid down for VNIR-radiometry measurements of burnt soil. The advantages of this non-destructive methodology (quickness, cheapness and precision) make VNIR radiometry a tool of great potential for estimating fire severity. The radiometric method developed has also proven to be more sensitive to fire effects than estimations made by traditional laboratory techniques.

It should be noted here that the tests for this study were conducted in the laboratory under controlled conditions, cancelling out external factors (constant lighting source, minimum diffuse dispersion, eliminated interference, etc.). These study results are therefore not directly applicable to measurements made in the field or on real fires. Many aspects remain to be examined before this technology can be transferred from its current state to possible final use in real fires. Results to date, however, have laid down the necessary base for a thoroughgoing study of field radiometry for determining the properties of burnt soils.

These advances are particularly important in the current scenario of climate change. According to the forecasts of the Intergovernmental Panel on Climate Change future conditions are likely to be even more adverse: longer summers, more droughts and heat waves. Witness, indeed, the increase in the number and size of forest fires in recent years in the Mediterranean area (10), and this trend is thought likely to hold steady or even worsen in coming years. The study of forest fires, including their effects and post-fire regeneration processes, is therefore increasingly important to ensure proper fire management.
Figure 7. Proposed research phases on the basis of results to date. The work presented herein corresponds to phase 1.

In light of the promising results of this project, the authors consider that the following research phases should now be tackled (figure 7). The second phase would involve setting up a field VNIR radiometry methodology for in situ assessment of fire severity in a quick, precise and efficient way. Phase 3 would then investigate the possibility of using remote sensing techniques and remote-platform images for building up forest fire severity maps. In the first phase (carried out in this project) all the radiometric measurement parameters were well known and even established by users themselves, thereby maximising measurement efficiency. In the second phase of field radiometry, however, factors come into play that are beyond our control (e.g. the amount of radiation falling on the sample, cloud cover on measurement days or the angle of solar inclination). In this phase the knowledge acquired in the experimental laboratory phase (phase 1) would help to offset the drawbacks of this lack of control over the measurement conditions. Likewise, the knowledge acquired in phase 2 would help to offset the greater restraints of phase 3.

The use of remote sensing techniques would offer, among other advantages, the chance of finding out and studying the spatial distribution of fire severity throughout a whole territory. The research carried out in the Centro de Investigación del Fuego, therefore, not only inputs results of great interest per se (in relation to the fire’s effects on the soil and the potential for estimating these effects with radiometric techniques), but also paves the way for future research within the blueprint proposed here. The findings of this study and also the advances in terms of methodological aspects represent the start of a line of research of great interest for the management of burnt areas. Indeed, precise determination of a fire’s severity is crucial for taking decisions and the application of palliative measures.

TO FIND OUT MORE

6. Hartford, R. A.; Frandsen, W. H. . When it’s hot, it’s hot ... or maybe it’s not (surface flaming may not portend extensive soil heating). International Journal of Wildland Fire 1992; 2: 139-44.


Archaeoseismology involves the study of past earthquakes by analysing archaeological sites, furnishing previously unknown information on seismic events that might not even have been recorded in history. This data can help to ascertain the seismic danger of relatively stable areas with long return periods of highly destructive earthquakes, such as the Iberian Peninsula.

Throughout the eighties and nineties of last century there was a stream of multidisciplinary research projects dealing with different aspects of archaeoseismology (Rapp, 1982; Stiros, 1988 a and b; Stiros and Jones, 1996; Nikonov, 1988; Guidoboni, 1989).

One of the main drawbacks of this relatively new science, however, is precisely that there is very little to go on as reference (excluding perhaps the work of Stiros and Jones, 1996). To fill this gap Rodríguez-Pascua et al (2009, 2011) made a bibliographic compilation of the main earthquake effects in archaeological sites of Europe and Asia, establishing a structured classification of the commonest seismic effects observable in archaeological sites (Earthquake Archaeological Effects or EAE for short) (Fig. 1).

Analysis of the seismic effects in archaeological sites or historical buildings is a multidisciplinary analysis (Fig. 2); it has to take into account fundamental aspects such as determination of the processes that might produce these deformations, the dating of the deformation structures or the available historical documentation.

Identification of Earthquake Archaeological Effects (EAE)

Identification of the damage is one the most important steps in the analysis, since it is the phase in which a suitable identification has to be made of all the possible earthquake effects. This necessarily involves a trawl through historical
Archaeoseismology involves the study of past earthquakes by analysing archaeological sites, furnishing previously unknown information on seismic events that might not even have gone down in the historical record.

The classification of earthquake archaeological effects (EAE) proposed by Rodríguez-Pascua (2009, 2011) (Fig.1) is used to identify the damage; this breaks down the effects into co-seismic effects, produced as a result of the direct, seismic-wave-induced earth movement (geological effects and effects on the building fabric), and post-seismic effects, meaning all effects occurring after the earthquake itself or measures taken by affected societies to repair past damage or ward off the effects of any future earthquakes. This identification has to take full account of all archaeological and historical studies of the area for two main reasons: firstly, to interpret the structures correctly and, secondly, to date them reliably and hence be able to assign them to a specific earthquake. Many of the recorded effects could have a multiple origin; this ambiguity can be ruled out by quantification of the deformation.

Likewise, the post-seismic effects can provide many insights to help us make sense of the visible deformation and its origin, even if it can no longer be analysed by means of deformation quantification techniques. There are localities where the occurrence of destructive earthquakes is still patently obvious in the buildings and post-quake repairs.

A classic example of a locality of this type is the city of Morelia (formerly Nueva Valladolid), state capital of Michoacán (Mexico), where systematic use has been found of earthquake-resistant construction methods in the reconstruction of masonry-block buildings. There are records of destructive earthquakes that affected large zones of Michoacán, including the city of Morelia, in the sixteenth and nineteenth centuries.
In Morelia an inventory has been made of many examples of earthquake damage reconstruction and the use of interlocking masonry blocks (post-seismic construction effects) in seventeenth and eighteenth century buildings. Although this construction technique may in theory stem from various causes, some examples observed in this Mexican city show the true objective of using interlocking masonry blocks here: the reduction of infrastructure damage caused by horizontal charges of seismic origin.
Take the example of the old Convento de San Diego, repaired after the 1856 earthquake of Pátzcuaro, with a recorded intensity of IX out of a scale of XII on the MSK scale.

This convent, dating originally from the mid eighteenth century (1768), was rebuilt in 1894 after the abovementioned earthquake. Its whole main front shows systematic use of interlocking masonry blocks, completely breaking up the horizontal tiers, especially on the ground floor (Fig. 3).
Figure 3. a) Detail of the 1884 reconstruction of the main front of the old Convento de San Diego (Morelia, México), with application of earthquake-resistant building techniques; (b) the reconstruction dates from the end of the nineteenth century (1895); (c) state after the great earthquake of Pátzcuaro (1856), which shook the towns of Pátzcuaro and Morelia. The main front reconstruction shows systematic use of interlocking masonry blocks (d).

Analysis of EAE deformation
Quantification of the deformation of the earthquake archaeological effects is based on analysis of the EAEs to gain insights into the deformation process produced or induced by the earthquake; i.e., the co-seismic effects: both the geological effects (a) and the building fabric effects (b) (see Fig. 1).

Classic structural geological techniques are used to ascertain the deformation of geological structures (a, geological effects). These enable us to establish the degree of uniformity present in the supposedly earthquake-caused deformation, thereby cutting down the uncertainly in the identification of the processes that have caused the recorded deformation.

This article presents the methodology developed for quantifying the earthquake-induced deformation in building fabric. This study involves application of techniques similar to those used in structural geology. The study results enable us to establish the degree of uniformity present in the supposedly earthquake-caused deformation, thereby cutting down the uncertainty in the identification of the processes that have caused the recorded deformation.

The methodology applied to the analysis of earthquake-caused deformation in building fabric in archaeological sites is broken down into various phases (Giner Robles et al., 2009) (Fig. 4):

- Determination of the data type. Before analysing the observed deformation we need to consider a series of factors related to the data we are going to compile. These factors mainly involve definition of the analysable parameters to obtain deformation tensor data and ascertain properly the kinematics of the deformation.

- Quantification of the deformation in each structure analysed, applying geological structural analysis techniques. The orientation of the deformation tensor is defined, characterised by its two main axes in the strain field: ey (direction of maximum horizontal shortening) and ex (direction of minimum horizontal shortening).

- Analysis of the defined tensors for each one of the EAEs (a single result for each type of structure described on the archaeological site), thereby cross-checking the site-wide consistency of the data in due accordance with the type of structure.

- Joint analysis of the archaeological site to assess the uniformity of the results across the whole site and thereby ascertain the cause of the deformation.
Earthquake Archaeological Effects EAE

Figure 4. Methodological scheme proposed by Giner-Robles et al. (2009) for quantitative analysis of the deformation present in the structures of an archaeological site (EAE) (Rodríguez-Pascua et al., 2009, 2011). Once the analysis has been made, the results are studied along with the rest of the information from the archaeological site: post-seismic effects, deformation dating, analysis of historical documents, etc. (see Fig. 2).

Figures 5 and 6 show some examples of the kinematic interpretation of structures, allowing us to establish the orientation of the damage-causing deformation tensor.
Figure 5. Idealised schemes of deformation analysis in arches and lintels. a) Deformation of seismic origin that shifted the keystones horizontally; the direction of maximum horizontal shortening (ey) is analysed in a similar way to that of tilted walls. b) Deformation of seismic origin causing dropped keystones; the direction of ey lies at an angle of less than 45º vis-à-vis the plane of the arch-containing wall.

Figure 6. Analysis of deformation in structures of fallen and oriented columns. The direction of maximum horizontal shortening (ey) is parallel to the fall direction of the columns. In this case even the directionality of the damage can be established, defined by the column fall direction.
Examples of application of the methodology

A description is now given of some examples of application of the methodology in a few historical buildings and archaeological sites of the Iberian Peninsula (Giner-Robles et al., forthcoming)

Astorga Cathedral (León)
Building work on this cathedral began in the fifteenth century and it suffered severe damage as a result of the Lisbon earthquake of 1755. Copious damage is described in the missive sent by the Alcalde Mayor (chief magistrate) of Astorga to the court on 21 November 1755, 20 days after the earthquake struck (Martínez Solares, 2001).

Much of this damage is no longer visible because it was repaired in the past; the cloister, for example, was totally reconstructed after the earthquake. Some analysable co-seismic structures are still visible, however. Prime among them is the displacement of masonry blocks in the side columns holding up the nave (Fig. 7); there are in fact historical records of this damage. These shifts can be analysed as displacement vectors, directly determining the direction of maximum horizontal shortening (ey) (parallel to the vector), and even the directionality of the damage (in this case towards the southwest).

Another of the visible effects is the dropping of the upper keystones of a small rose window in the lunette of the northern chapel of the cathedral crossing (Fig. 7a).
Figure 7. Co-seismic effects inside Astorga Cathedral (León). a) Displacement of the keystones in a small rose window in one of the side chapels. b) Decimetric displacement of the masonry blocks in one of the columns separating the crossing from the nave. c) Cumulative displacement of the masonry blocks making up one of the columns, visible displacement even with signs of thoroughgoing repairs. d) Masonry block displacement in the connection of the nave with one of the south facing windows.

Coria Cathedral (Cáceres)
The Catedral de Santa María de la Asunción of Coria (Cáceres), built between the fifteenth and eighteenth centuries,
suffered severe damage from the Lisbon earthquake of 1755.

In some cases the historical descriptions are so detailed that they enable us to reconstruct some earthquake-related events; these can then give many insights and even allow us to enhance the analysis of visible co-seismic effects.

In the case of this cathedral, the description of the collapse of the lantern roof and cupola of the tower clearly details the damage (letter from the Bishop of Coria to the court on 7 November 1755 describing cathedral damage) (Martínez Solares, 2001) (Fig. 8). The presence of rotated structures in some of the cathedral pinnacles (Martínez Vázquez, 1999) suggests that the collapse of the lantern was due to its rotation with respect to the cupola, bringing it tumbling down.

Figure 8. Interpretation of the damage suffered by the upper structure (lantern and cupola) of the tower of the Catedral de Santa María de la Asunción of Coria (Cáceres) as a result of the Lisbon earthquake. Without the historical description of the damage we would have been unable to determine the range of orientations of maximum horizontal shortening (ey) for this collapse, since post-quake repairs covered up all co-seismic effects, none of which are visible today. Detail of a rotation structure in one of the cathedral pinnacles (Martínez Vázquez, 1999). Note the lefthand (anticlockwise) rotation of the masonry blocks making up this pinnacle. The description of the collapse of the tower lantern suggest that it was due to the previous rotation of the lantern over the cupola.
Identification and recording of the effects of ancient earthquakes in the historical and archaeological heritage can raise public awareness of seismic danger.

In the Roman archaeological site of Baelo Claudia (Cádiz) previous studies had defined the occurrence of two earthquakes with no historical records in the period running from the 1st to 3rd century BCE. (Silva et al., 2005). This archaeological site was analysed by means of multidisciplinary collaboration between various experts (archaeologists, historians, geologists, architects, etc); this collaboration brought about diverse damage and effects that seem to have been caused by nearby earthquakes; this is especially true of the archaeological data (e.g. abandonment of parts of the city, presence of destruction layers, etc.).
Figure 10. Co-seismic effects in the building fabric as recorded in the Roman archaeological site of Baelo Claudia (Cádiz). a) Fallen and oriented columns affecting the walls of the basilica in the forum area of Baelo Claudia (Sillères, 1997). In many cases the original material of the archaeological digs has to be checked to define the different effects correctly. b) In this case the basilica zone has been restored and the columns located in their original pre-collapse position. c) Fragment of the eastern wall of the city, folded and titled. On some occasions we might find two effects on the same structure. d) Folds and pop-ups in the regular pavement of the forum plaza. e) Fragment of the eastern tilted wall. d) Dropped and displaced keystones in a linteled window in one of the public buildings of the forum.
The EAE deformation found on this archaeological site was analysed to quantify this deformation and thereby confirm the hypothesis of past destructive earthquakes on this site, as suggested by other multidisciplinary techniques and analyses (Silva et al., 2009).

Application of the deformation analysis to Baelo Claudia focused, firstly, on recording all EAE in the site zone. Once all the apparently earthquake-related deformation had been recorded a determination was then made of the orientation of the maximum horizontal shortening direction ($ey$) of each one of the individual structures. An analysis of deformation for each type of EAE was then carried out for the whole site (Fig. 11).

Finally, a joint analysis was made of the $ey$ orientations in the whole site. Once other processes had been ruled out, this analysis established the seismic origin of the deformation. The results also chime in with those obtained by other authors (Silva et al., 2005 and 2009). This type of analysis also allows us to define zones in which deformation paths have been reoriented due to the presence of structures such as pipelines, foundations, etc.
Figure 12. Joint analysis of the results obtained from individual study of the EAE appearing in the archaeological site of the Roman city of Baelo Claudia (Cádiz). a) Representation of the orientations of maximum horizontal shortening (ey) as deduced from individual EAE analysis. b) Common result of the ey orientation for the whole site. c) Representation of the deformation paths (ey red lines; ex blue lines) in the city’s forum area. These results show a clear uniformity, bearing out the reoriented paths in: the area of the decumanus maximus (D), caused by underground drainage; the area of the forum plaza (B), caused by the existence of regular pavements; and the zone of the Temple of Isis (A), related to a very superficial co-seismic gravitational process affecting this part of the archaeological site (Silva et al., 2009).

Instrumental earthquake analysis

Most of the structures and effects considered in this classification have been described in various archaeological sites as a result of earthquake-caused damage. Nonetheless many of these effects can be observed in historical buildings affected by instrumental earthquakes (Fig. 13).
Figure 13. Comparison of damage suffered by seismic activity in: (a) pavement slabs of Armagh Street (Christchurch, New Zealand) (earthquake of 22 February 2011) (Photo: Juan Miguel Insúa Arévalo); b) pavement of the forum of the Roman archaeological site of Baelo Claudia (Cádiz), a city affected by an earthquake in the third century (Silva et al., 2009). In both cases the pavement is seen to buckle into anticlinal and synclinal folds with pop-ups. In the case of the Christchurch earthquake structure this deformation is associated with liquefaction process of underlying sand.

The analysis of damage caused by instrumental earthquakes such as that of Lorca (Murcia), which occurred on 11 May 2011, could be key in the interpretation of seismic damage in archaeological sites (Figs. 14 and 16). The preliminary analysis of the effects of this earthquake enables us to calibrate the developed methodology, establishing the margins of error in calculating the deformation parameters.
Figure 14. Damage to the tower of the 15th church Iglesia de San Juan in Lorca (Murcia).
Figure 15. Analysis of the observed damage to the tower of the iglesia de San Juan. The sides of the tower running NW-SE 170° show more damage than those running in other directions. Determination of these orientations enables us to quantify the earthquake-caused deformation.

In the case of the Lorca earthquake, two historical buildings of the city were chosen: the church called Iglesia de San Juan (Figs. 14 and 15) and the St. Clare Nunnery (Monasterio de las Clarisas) (Figs. 16 and 17).
Figure 16. Damage to the Monasterio de Santa Ana y la Magdalena de las Clarisas, in Lorca (Murcia). a) Bird’s eye view of the nunnery buildings and location of the main damage. (b) and (h) Conjugated fractures in walls of various buildings of the nunnery; c) Fracture and displacement of the NW wall of a building annexed to the church; fallen and oriented walls in different structures: (d) in a small belltower; (e) in the NW wall of the nunnery church; (g) in a building annexed to the church, and in one of the corners of the main front (g).
Analysis of damage in instrumental earthquakes such as that of Lorca (Murcia), which struck on 11 May 2011, could be key in the interpretation of seismic damage in archaeological sites.

Conclusions

The archaeoseismological analysis of archaeological sites and historical buildings can give us crucial insights for calculating seismic danger.

Analysis of observable deformation in the various effects recorded on site, with application of classic geological structural analysis methodologies, enables us to quantify the deformation present on the site.

The results of the archaeoseismological analysis of the deformation related to the surface seismic-wave propagation front facilitates analysis of the consistency of the deformation with respect to probable seismogenic sources, whether known or unknown active faults.

Analysis of the effects of recent earthquakes recorded instrumentally in historic enclaves or archaeological sites furnishes a great deal of information about the kinematics of the processes involved. Instrumentation tells us the focal parameters of the earthquake; this then makes it possible to calibrate the EAE, which, applied inversely to palaeoseismological and archaeological earthquakes, enables us to reduce the degree of uncertainty of the analysis and even consider such parameters as epicentre location and maximum intensity. These parameters can then be used in calculating seismic danger, implementing the results in macroseismic scales based on the geological and environmental effects of these earthquakes, such as the macroseismic...
Results of the archaeoseismological analysis of the deformation help to weigh up the consistency of the deformation with respect to probable seismogenic sources, whether known or unknown active faults.

Archaeoseismological analysis is now another arrow in the quiver for ascertaining and heading off seismic risk in areas of long return periods such as the Iberian Peninsula. In these slow areas the return periods of big quakes means that the public is not really aware of the seismic danger of the area they live in. Such a long lapse of time dampens public perception of the danger and limits society’s preparation against event of this type.

In our opinion the identification and analysis of earthquake effects and EAE in the historical and archaeological heritage could help to make the public more aware of the existing seismic danger in certain areas of the Iberian Peninsula and also the degree of exposure to destructive earthquakes.

This information on the seismic danger as perceived by the population is of great help not only in mitigating possible damage but also establishing emergency plans by the public authority.

All too often historical architecture restoration programmes completely eliminate these seismic effects. We consider these effects to be of great historical and didactic importance, however, and they could even be said to form part of our cultural heritage.

Effects of destructive earthquakes, such as the Lisbon 1775 quake, are still visible in many historical buildings and archaeological sites in Spain. All too often historical architecture restoration programmes completely eliminate these seismic effects. We consider these effects to be of great historical and didactic importance, however, and they could even be said to form part of our cultural heritage.

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The use of LEDs as lighting sources is growing exponentially, not only as domestic lighting but also in terms of personal devices such as smartphones, computer screens, household appliances, etc. The main drawback of white-light emitting LEDs, however, is their high content of blue wavelength radiation, which is harmful to the visual system. This project involves the design of a lighting device formed by LEDs of different spectral characteristics to check if they cause retina damage, especially in retinal pigment epithelium cells. Our experiments have shown that light exposure from all LED sources increases the percentage of light-induced cell death, especially in cells exposed to white and blue light, which record a 92% and 94% cell-death increase, respectively, in comparison to a non-exposed control group. The study concludes that exposure to high intensity LED light during light/dark cycles harms retina cells.

By EVA CHAMORRO, CRISTINA BONNIN, LUIS LUCIO LOBATO-RINCÓN, JUAN JOSÉ NAVARRO-VALLS, GUILLERMO RAMÍREZ-MERCADO, CAROLINA NAVARRO-BLANCO, CELIA SÁNCHEZ-RAMOS.

Introduction and historical background

The first Light-Emitting Diode (shortened to LED) was created in 1927 by Oleg Vladimírovich Lósev (1903-1942), but LEDs were not taken up commercially until 1962, when a relatively low-intensity red LED with an emission frequency of about 650 nm was developed. In the seventies new spectrum colours were brought in (green and orange), as well as infrared LEDs. It was not until 1993, however, that blue LEDs were developed thanks to the research work of the scientist Shuji Nakamura, who discovered a cheap blue-LED manufacturing process based on the compounds gallium nitride and indium nitride. This discovery paved the way for the subsequent development of the white LED from blue LEDs with a phosphorous coating.

LEDs were initially used in remote controls for television sets, hi-fi systems, etc. Their use steadily took off and is now widespread in electronic devices, household appliances, remote controls, detectors, mobile phones, signage, information panels, liquid crystal display screens of mobile phones, calculators, electronic agendas, among others. For domestic lighting purposes white LEDs have been developed as an alternative to traditional light bulbs, on the strength of their undoubted advantages like low energy consumption, low voltage, low temperature, quicker response capacity and longer useful life. A recent article by Behar-Cohen et al (2011) predicts that incandescent lighting sources will be phased out by LEDs in coming years, disappearing completely in Europe by September 2016 [1]. Nonetheless, the main, unresolved problem posed by white-light emitting LEDs is their high content of blue wavelength light (the most energetic) and high luminance.

It has been scientifically proven that blue light (short wavelengths) has a negative effect on the eyes (retina). Light-induced injuries have traditionally been broken down into three types: photomechanical (light wave shock effect), photothermal (local wave-induced heat) and photochemical (change in the macromolecules). Light-induced retina changes are by now understood with a fair amount of precision [2,3].
LEDs have been widely taken up for use in electronic devices, household appliances, detectors, mobile phones, signage, calculators and electronic agendas, among others. Recent publications have weighed up the toxic effects of light on retinal pigment epithelium cell cultures [4,5]. The main aim of these studies has been to ascertain the cell survival rate after light-radiation exposure. To date, however, there have been no studies to assess the harmful effect of LED light on ocular structures. This is of great interest, however, due to the sheer number of hours that people are exposed throughout their lifetimes to light sources of this type. There would therefore seem to be an urgent need for studies of human organs exposed to this light, i.e., the eye and especially the retina, which is the most vulnerable zone of the eye and is essential for the power of sight.

The main aim of this study is therefore to determine the light-induced harm (phototoxicity) caused by LEDs on the retina in vitro to find out the repercussion on the human visual system.

**Materials and methodology**

**Emitter: LED lighting device**
A lighting device has been designed comprising five differentiated zones separated off from each other by discriminating barriers of a white material. Each one of the zones contains a LED producing light of irradiance 5mW/cm² but with different spectral characteristics: blue LED (468 nm), green LED (525 nm), red LED (616 nm), white LED with a colour temperature of 5400ºK. The last zone was made up by a control group of cells that had not been exposed to any light (Figure 1).

**Receptor: human retinal pigment epithelium cells**
Retinal pigment epithelium cells from healthy human donors were grown in a culture medium, a sine qua non for in vitro cell culture. The cells were sown in 96-well plates at a density of 5000 cells per well. The culture medium was replaced every 24 hours to pre-empt evaporation from the heat given out by the light. The retinal pigment epithelium is a hexagonal layer of cells that is essential for the power of sight; alternation thereof produces retinal degeneration, impairment of the visual function and even blindness.

**Phototoxicity experiment**
The retinal pigment epithelium cells were exposed to the different light sources during 12 hour/12 hour light/dark cycles. After the exposure the cells were treated with specific toxicity-assessment procedures and observed by fluorescence microscopy (BD Pathway 855, Becton, Dickinson and Company).
DAPI staining was used to quantify cell survival; this technique, ideally suited for the cell count, involves a colorant that stains the cell nuclei and is excited with ultraviolet light to produce strong blue fluorescence when joined to the DNA.

The indicator used to evaluate the light-induced cell death (apoptosis) was caspase-3 and -7 activation, since these enzymes are involved in apoptosis regulation and execution.

Statistical treatment
Each experiment was repeated at least twice. The values are given as mean ± standard deviation. The data were analyzed by Student’s t-test using the statistical software Statgraphics Centurion XVI.1 (USA). P-values of less than 0.05 were considered to be significant.

Results
Cell survival
After the exposure period during three 12 hour/12 hour light/dark cycles the cell nuclei of the retinal pigment epithelium were DAPI-stained to count the number of cells per well.

The non-irradiated cells grew well in the plate wells but irradiation with LED light inhibited cell growth. Blue light produced a very significant reduction in the number of cells, although there was also an observable phototoxic effect for green and white light. In the case of red light no statistically significant differences were observed (Figure 2).

Figure 2. Cell survival of the retinal pigment epithelium cells. Graph showing the mean ± standard deviation of n=2-5 experiments. Representative images obtained from fluorescence microscopy. The asterisk (*) shows statistical differences when compared with the control group (p<0.05, Student’s t).

Apoptosis (light-induced cell death)
Caspase-3 and -7 activation was the indicator used to assess light-induced cell death, since these enzymes are involved in the apoptosis process. The experiments showed that light exposure increases the percentage of apoptotic cells for all LED light sources, especially in the cells exposed to blue and white light, in which there was a 92% and 94% increase, respectively, of apoptotic cells (cell death). Microscope images show caspase activation as a pinkish colour around the blue DAPI-stained nucleus (Figure 3).
Our study shows an appreciable reduction in cell survival and concomitant increase in light-induced cell death

Discussion

The first evidence of light damage to the human retina dates back to 1912 in Germany when thousands of people suffered retina lesions after watching a solar eclipse [6]. Two wavelengths of the visual spectrum have traditionally been blamed for phototoxic damage: class I damage coincides with the absorption spectrum of rhodopsin whereas class II damage peaks in the short wavelength region (accounting for the concept of violet-blue light hazard). Two mechanisms of photochemical retina damage have therefore been proposed: one put forward by Noell in 1965 and the other by Ham in 1976. Table 1 shows the main distinguishing features of both [7-9].

Werner et al (1989) described different degrees of RPE cell damage in patients scheduled to undergo enucleation who voluntarily looked at the sun. No significant photoreceptor alterations showed up, however, accounting for the sound vision after exposure [10]. The retinal pigment epithelium regenerates rapidly whereas photoreceptors begin to degenerate, sometimes even disappearing completely after light exposure [11].

In recent years diverse publications have focused on evaluating the phototoxic effects of light on pigment epithelium cell cultures. The main objectives of these studies was to assess cell survival of epithelial cells after light exposure. Some studies also looked at other factors such as mitochondrial activity, DNA damage, levels of the endothelial growth factor and other salient aspects.

For example, in the study of Godley et al (2005) cell cultures were irradiated with light comprising wavelengths from 390 to 550 nm, with an irradiance of 2.8mW/cm2, the exposure time ranging from 0 to 9 hours. Results showed no differences in cell survival after three hours of light exposure; after 6-9 hours, however, there was an appreciable reduction in mitochondrial respiration. Another finding of this study was an increase in the production of oxygen reactive species after one hour of light exposure and also DNA damage after three hours of exposure, falling away at six hours, indicating the start of DNA repair (adaptive response) [4].

Table 1. Distinguishing features of the mechanisms of photochemical retina damage put forward by Noell in 1965 and Ham in 1976.

<table>
<thead>
<tr>
<th>Type I or blue-green type or Noell type</th>
<th>Type II or blue-UV type or Ham type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced after long exposure to low light intensities (&lt;1mW/cm²)</td>
<td>Produced after short exposure to high light intensities (&gt;10mW/cm²)</td>
</tr>
<tr>
<td>Initial damage found in photoreceptors</td>
<td>Initial damage found in retinal pigment epithelium cells</td>
</tr>
<tr>
<td>Most harmful wavelengths: equivalent to the absorption spectrum of the visual pigment (rhodopsin)</td>
<td>Most harmful wavelengths: short wavelengths of the visible spectrum (violet-blue)</td>
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</table>
The study concludes that exposure to LED light during light/dark cycles harms retinal pigment epithelium cells.

To date, however, no studies have looked into the phototoxic effect of LED-emitted radiation on retinal cells. Our study has evaluated cell survival and cell death of the retinal pigment epithelium produced by medium-intensity LED light (5 mW/cm²). The results of our experiments show an appreciable LED-light-induced reduction of cell survival and concomitant increase in cell death, the phototoxic damage being greater at shorter wavelengths.

It should be pointed out here that the EN 62471 standard classifies lighting sources according to the phototoxic risks (from ultraviolet to infrared radiation), establishing four risk groups according to the maximum permitted exposure time:

- 0 risk (no risk). When the maximum exposure limit is higher than 10,000 seconds.
- Risk 1 (low risk). When the maximum exposure limit falls between 100 and 10,000 seconds.
- Risk 2 (moderate risk). When the maximum exposure limit falls between 0.25 and 100 seconds.
- Risk 3 (high risk). When the maximum exposure limit is less than 0.25 seconds.

On the basis of this standard, Behar-Cohen indicated that a blue LED with an intensity of over 15 W belongs to risk group 3; if the light intensity is 0.07 W it belongs to group 1. LED lighting sources of everyday use for the general public are classed as risk group 2 (in comparison to conventional lighting sources that belong to group 0 or 1). He also found that the amount of blue light emitted by a white LED is 20% higher than daylight of the same colour temperature [1].

**Conclusion**

Exposure to LED light during 12 hour/12 hour light/dark cycles, especially in the shorter wavelengths, harms retinal pigment epithelium cells. Future studies are now needed to ascertain which intensities, wavelengths and exposure times of LED lighting devices are lethal and non lethal for retinal tissue.

**ACKNOWLEDGEMENTS**

This research has been funded by FUNDACIÓN MAPFRE (Research grants 2011).

**TO FIND OUT MORE**

Simulation-based behaviour-training in occupational risks prevention

This article describes the Asociación Nuclear Ascó-Vandellós II A.I.E. (ANAV)’s behaviour-simulation project as part of prevention-of-occupational-risks training. This project, a trailblazer in Spain, achieves effective integration of occupational risks prevention into induction job training.

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Power plants involve facilities, equipment and processes that might be of great complexity; they also generate risks that could potentially affect plant workers. In the case of a nuclear power plant the complexity is even greater and there are specific risks such as exposure to ionising radiation; these risks determine how the work is to be carried out (time restraints on carrying out certain tasks, etc.). Furthermore the human factor has to be taken into account in all these risks, a factor that often looms large in accidents and incidents.

Another complicating factor is that companies of this type need to consider these risks not only in normal working conditions but also during fuel-reloading and maintenance activities when the station is shut down and the number of workers involved is multiplied. Risk situations also have to be taken into account. In a nuclear power plant, therefore, worker training plays a crucial role within the whole set of preventive procedures.

As in other firms, training has to be carried out under the aegis of article 19 of the Spanish Prevention of Occupational Risks Act 31/1995 (Ley de prevención de riesgos laborales), covering the theory and practice of the whole set of risks to which workers are or might be exposed when carrying out their work. Nonetheless, there are in fact few examples of the practical side being dealt with during induction training on occupational risks. In most cases training is restricted to the classroom exposition of a set of information and tips, etc, without proper integration of this knowledge into the workers’ daily tasks and without considering the abovementioned practical side. Along these lines the Spanish Strategy of Health and Safety at Work 2007-2012 (Estrategia Española de Seguridad y Salud en el Trabajo 2007 - 2012) holds up training as “one of the essential pillars” of this strategy and ipso facto of the prevention of occupational risks in Spain. Objective 6 of this strategy underlined the need of having duly qualified and skilled workers, pointing out also that part of this qualification should “consist of soundly based training in the prevention of occupational risks, not only from the theoretical point of view but also in terms of the effective practice thereof”.

Cultural Change in Safety
The appearance in 2009 of ANAV’s Organisational, Cultural and Technical Reinforcement Plan (Plan de Refuerzo Organizativo, Cultural y Técnico: PROCURA) represented a complete rethink of the company’s safety policy as carried out hitherto. This plan, incorporated as a top-priority activity within ANAV’s strategic framework, includes a coordinated set of actions designed to reinforce organisational and cultural aspects, leading to an improvement in ANAV’s operational safety and reliability. One of the ideas spawned by Plan PROCURA was to create a behaviour simulator (hereinafter, a human factor simulator). This simulator would stress the overriding importance of preventing human error in the operation of the nuclear power plant and show how the prevention of such errors would improve management of health and safety. It was therefore considered that simulation of the workers’ activity inside the plant would be a good option for moulding worker behaviour, guiding them towards safe behaviour through a structured learning process.

The human factor simulator has been conceived as a fundamental tool for improving the training of personnel working in the nuclear power plant, whether own staff or the workers of contracted firms. It involves the holding of practical sessions in facilities containing similar equipment to that which exists in the nuclear plant. The idea is to drill workers in simulated situations that are similar to those they will find when carrying out their work, with the overall aim of encouraging safe behaviour and preventing human error. The human factor simulator was designed in light of the operational experience in the nuclear sector, taking its inspiration from the INPO models (Institute of Nuclear Power Operations) and various models of European and North American nuclear power plants containing simulators of this type. The simulator design process involved a multidisciplinary working team (areas of organisation and human factors, maintenance, planning, radiological protection, operation, training and prevention of occupational risks) which compiled information on visits to the various nuclear plants.

### Training Stations

The simulator components are housed in a 1106 m² building; it comprises eleven training stations where most of the simulator training is carried out.

2. Working at height.
3. Exclusion of foreign bodies.
4. Fire protection.
5. Radiological protection.
6. Clearances.
7. Human error prevention techniques.
8. Hoisting and movement of loads.
11. Personal protection equipment and signage.

The simulator also has a hydraulic loop, a mock-up area, workshop-classrooms for practical assembly- and disassembly-exercises on the most common plant equipment and a sample of tools, personal protection equipment and banned material in the nuclear power plant. The idea of the latter is to bring fully home to trainees the reasons for the prohibition of this material.

All these facilities between them recreate the most usual manoeuvres in a nuclear power plant and drill human-error prevention practices, thereby reinforcing safe behaviour. Greater verisimilitude has been achieved by using recently replaced working equipment from the nuclear power plants of Ascó I, Ascó II and Vandellós II. On the basis of these facilities and working equipment a set of scenarios has been designed for detecting possible errors and unsafe behaviour and reinforcing safe working habits. These scenarios have been built up from operational experience of this plant and others. A crucial part in their design was played by ANAV’s Prevention of Occupational Risks Department with the aim of reinforcing preventive habits among workers.

After the simulator had actually been built, it was then vetted by all the departments involved in its design and conception, with a final validation by INPO. Each scenario was also vetted by the heads of the corresponding Organisational Units and by their training coordinators and instructors.
Worker Training

The training process kicks off with the presentation of the whole training activity by an ANAV Manager, whose presence reinforces management expectations of the activity. After a brief explanation by the instructor of the basic aspects to be taken into account in the plants under review, a start is then made on task simulation in each one of the previously designed scenarios.

The task is carried out following the same organisational scheme as in real operational conditions: first and foremost an indication is given of the internal procedures to be followed and a work package is handed out with work orders and any corresponding permits. A pre-job meeting is then held with all workers involved, analysing and preparing the task to be carried out and the roles of each worker. Any necessary tools are then taken up and personal protection equipment donned before starting the tasks themselves. After the tasks have been completed, the instructor meets up with the supervisor to point out any deviations that might have come to light in relation to his/her responsibilities and duties in carrying out the task, solving any problems that might have cropped up. Finally the supervisor meets up with the workers in a post-job debriefing (with the instructor in attendance) to analyse any faults and discuss how to improve task execution.

The inclusion of a supervisor in each of these training activities is paramount. The supervisors’ duties, within ANAV’s organisation, include reinforcement of proper activity, the correction of improper practices and the encouragement of participation and communication between the personnel under their charge and the rest of the personnel. Their inclusion in these training activities cements the supervisors’ role in aspects such as the prevention of occupational risks, given their vital role in carrying out the real tasks. Participation of supervisors in the training activities also chimes in perfectly with the need of across-the-board integration of all the firm’s hierarchical levels into occupational risk prevention after the 2003 amendment of the Ley de Prevención de Riesgos Laborales.

The instructor, apart from making the initial explanation, is responsible for monitoring the execution of the simulated task, bringing any shortfalls to the supervisor’s attention to act accordingly.

The drill ends with self-assessment by participants where they themselves analyse any mistakes made in carrying out the tasks, setting forth the correct way of carrying them out and improvements that might be tackled in the scenarios. This procedure means that the training process itself is fed back into a continual improvement of the training activity. Each drill lasts six hours, distributed among the various scenarios, workshop-classrooms, etc. varying to suit the particular training needs of the participating personnel in each case.

Faithful Scenarios

The scenarios have been conceived with the simulator stations and facilities in mind. Other conditions can be factored in to ensure that the scenario faithfully simulates plant situations: activation of alarms, the need of adopting forced postures, time restraints in carrying out the tasks or environmental factors such as high temperatures, high noise levels, etc). All these determining factors act as task impediments and bring the simulation even more closely into line with real working conditions inside the plant. Some small traps were even factored in, such as personal protection equipment or tools of the wrong sort or in a poor state, banned objects, etc, with the idea of applying the knowledge built up by the workers and safety logic, thus reinforcing recognition of those aspects that might impinge negatively on safety conditions.

As already pointed out, use of the simulator is not restricted to ANAV’s personnel but also takes in the personnel of contracted firms; training activities are therefore carried out by teams made up by multidisciplinary personnel.

As for future developments of the simulator, new scenarios will undoubtedly have to be phased in to incorporate information from incidents and accidents as they occur. New simulator uses will also have to be defined: recreation of accidents, trying out new working methods and training for carrying out critical tasks, among others, will all help in pinpointing the causes of accidents and incidents and ensure tasks are carried out more safely and in the shortest possible time. All this will undoubtedly be conducive to increased safety of the personnel and the plant itself.

In the first year of its operation a total of 1750 workers have now been trained in the human factor simulator, adding up to over 10,000 practical training hours. ANAV’s human factor simulator marks a milestone in the training of occupational risks prevention in Spain’s nuclear sector, in terms not only of its objectives and approach but also its design and execution budget (a million euros). Another notable feature is the integration in a single training activity of aspects such as the prevention of occupational risks, human factors and radiological protection. Factors such as the focusing of worker training
on error avoidance, participation of supervisors in the training activities and the huge number of risks and situations included all represent a great stride forward in terms of incorporating practical aspects into the training of occupational risks prevention.

The 11 stations of ANAV’s human factor simulator

ANAV’s human factor simulator comprises 11 training stations, each one of which simulates different scenarios from a specific part of the nuclear power plant posing its own particular risk. These are the following:

Station 1
Confined spaces

This has two separate spaces simulating a tank and a gallery or sewer. Practical working activities are carried out in them, rehearsing the steps to be followed in confined-space working and rescue techniques. Temperature conditions can be modified in this station (heat stress).

Station 2
Work at height

A training station prepared for explanation of the use of harnesses and ladders/stairs on site. Stress is laid on the scaffold identification tag number and prevention of falls from height in scaffold working.

Station 3
Exclusion of foreign bodies

This station drills practices to exclude foreign bodies and avoid the accidental introduction of potentially damaging objects into the equipment of the nuclear power plant.

Station 4
Fire Protection

Drills here involve the proper management of flammable material in due accordance with plant procedures (labelling, storage in airtight cabinets, etc). The station includes related signage and recreates measures for reducing the fire load in cubicles.

Station 5
Radiological protection
An analysis is made of the main principles of radiological protection and ALARA principles. A demonstration is also given of the entry into and exit from the radiological zone, the clothing to be worn and techniques to avoid contamination while dressing and undressing.

Station 6
Clearances

Station designed to steep participants in clearance and tagout procedures. Stress is laid on the various tagging systems and hold cards used during the clearance processes.

Station 7
Human-error prevention techniques

On a small console communication is drilled in three ways: the phonetic alphabet, abidance by plant procedures and other verifications and practices bound up with the prevention of human error.

Station 8
Hoisting and movement of loads

Load hoisting and movement drills are carried out on the simulator’s bridge crane, looking at sling type and layout, etc.

Station 9
Electrical risk

A cubicle recreates a motor control centre with electrical switches of varying power to simulate situations faced by operators of electrical equipment.

Station 10
Chemical products
Using a set of materials available in the plant, this station runs through the various types of recipient used in the plant, the correct labelling thereof, the use of safety data sheets and safety indications for the storage of chemical products.

Station 11
Personal protection equipment and signage

A study is made of the different types of personal protection equipment (PPE) used in the plant, obligatory standards, their application in plant signage, etc. Information is also included on evacuation routes and emergency telephones.

TO FIND OUT MORE

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This article presents a study of four fine-grained detrital sedimentary rock types (lutites) of the Cantabrian Basin, from 57 samples taken in seven sections. The interest of this study resides in the fact that they might contain a worthwhile amount of natural gas and/or make up a suitable CO₂ sequestration sink. Properties of these rocks were determined by mineralogical and geochemical techniques; the results show that the most suitable rock formation in terms of its natural-gas generation potential is the Paquete Fresnedo, which appears on the eastern limit of the Cuenca Carbonífera Central (Central Coal Basin). Although use of these rocks for CO₂ sequestration is not ruled out, saline aquifers would in theory be the best option.

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It goes well beyond the remit of this work to attempt any exhaustive analysis of short- and medium-term worldwide energy supply trends. There is already a host of detailed literature, most of it confirming a significant future contribution from fossil fuels. Best estimates point to a 44% rise in energy demand from 2007 to 2030. This rise would be met mainly by increasing the production of oil, coal (especially) and natural gas; this would in turn increase global CO₂ emissions from the current 31 Gt to 40.4 Gt by 2030.

Coal reserves are fairly evenly shared out worldwide, whereas 65% of natural gas reserves are owned by Russia and Middle Eastern countries (Iran, United Arab Emirates, Qatar and Saudi Arabia). The European Union has only 2.7%.


The sedimentary fine-grained rocks under study are made up mainly by quartz and phyllosilicates. The USA has been tapping into rocks of this type for natural gas for over a century. The United States has been tapping into the natural gas content of certain lutite levels (informally known as «shale») for over a century; this shale is a common rock type in sedimentary basins. Accumulations of this type, among others, are dubbed “Unconventional Natural Gas Resources”, in contrast to the generally worked fields (conventional), which include a hydrocarbon source rock, a reservoir rock and cap rock. One of the most characteristic properties of lutites is very low permeability; this rules them out as a good reservoir rock but they can in many cases make up a good cap rock.
Unconventional natural gas sources include shale gas; shale here plays the role of source rock, reservoir rock and cap rock simultaneously.

Geological CO2 sequestration also comes into play here as a partial emission-reduction solution, using the subsoil as a CO2 sink after a capture and injection process: the free CO2 would be injected as a supercritical fluid at depths of at least 800 metres, remaining stored there safely for a long period of time (hundreds to thousands of years).

The idea of carbon sequestration arose in the United States and Canada, where deep injection of hazardous liquid waste and deep geological storage of radioactive waste has been under study and even implemented for some decades now. The first industrial geological CO2 sequestration operation has already been carried out in Sleipner (North Sea, Norway). Since that time the company Statoil has been injecting 1 million tonnes a year into a saline aquifer (Utsira Formation) 1000 metres below the seabed. According to the figures of NETLs (National Energy Technology Laboratory of the US’s Department of Energy (DOE), CCS Worldwide Database (see www.netl.doe.gov/), there are now 254 geological CO2 capture and/or sequestration operations up and running in over twenty countries. In the abovementioned projects, and in the vast literature available on this matter, consideration has been given to four geological CO2 sequestration options, depending on the type of storage. In order of importance, these are the following:

- Deep-lying porous and permeable formations (or «saline aquifers»).
- Worked-out oil- and/or gas-fields.
- Deep coal layers, not economically exploitable.
- Sedimentary fine-grained rock (shale or lutite) rich in disperse organic matter.

The great majority of today’s demo projects are carried out in saline aquifers. Their main advantage is their huge storage capacity and good injectability. The specialised literature cites only studies underway into geological CO2 sequestration in shale or lutite, most of them in embryonic state in the US [1,2].

In light of all the above, this work has been carried out with two main aims:

- Determine whether or not the rocks under study contain worthwhile quantities of potentially recoverable natural gas.
- Estimate in which cases and sites these formations might be suitable for geological CO2 sequestration.

The location and properties of the rocks under study

This study has chosen four levels of lutite rock to ascertain their worthiness in terms of gas production and CO2 sequestration. Figure 1 shows the classic geological breakdown of the Cantabrian Zone into the various geological units. From west to east these units are called: Unidad de Somiedo, Unidad de La Sibia-Bodón, Unidad del Aramo, Unidad de la Cuenca Carbonifera Central (hereinafter, CCC), Cobertera Mesozoico-Terciaria, Unidad del Ponga and Unidad de Picos de Europa. Alonso et al. (2009)[3] have produced an interesting work discussing this classic breakdown and advocating a new scheme.
Tapping into the natural gas contained in rocks of this type would help to reduce Spain’s heavy dependence on foreign fuel sources.

Within the Unidad de Somiedo the Formigoso Formation was chosen for study (70 to 200 metres thick), made up by black and grey slate intercalated with wafers of bioturbated siltstone and sandstone (quartz sandstone), becoming more abundant towards the surface and with frequent graded lutite layers. See some of the specific works for more detail on this rock [5,6].

In the Unidad de La Sobia-Bodón, and specifically in the Bodón mantle, the San Emiliano Formation was sampled and studied, a predominantly terrigenous succession up to 2000 metres thick and dating from the carboniferous period (Namurian-Westphalian). It has thin limestone layers in the middle part and some coal layers in the upper part [7,8].

Two rock types were chosen as sample studies in the Unidad de la CCC:

- The Paquete Fresnedo, a predominantly lutite unit with smaller sandstone wafers (making up about 7% of the whole [9]) up to 470 metres thick, containing some turbidite intercalations and calcareous breccias and olistoliths, which, where present, are separated between two sizeable limestone levels called Caliza Masiva and Caliza de Montaña (or Calcaire des Canyons) (Barcaliente and Valdeteja Formations). The Paquete Fresnedo dates from the Carboniferous period (Westphalian A) and is laid out laterally through the Valdeteja Formation[10], forming wedge shapes where this formation exists.

- The Pizarras del Sueve Formation, which outcrops only in a narrow band between Rioseco and Sierra del Sueve, bordering on the CCC Units to the west and the Ponga region to the east. Although predominantly made up by shale and slate there are intercalated layers of siltstone and sandstone in the lower part of the succession. Its thickness is variable, ranging from 50 to 100 metres, averaging out at 60 metres. The most detailed study of this level has been written by Gutiérrez-Marco et al. (1996) [11].

Figure 1 shows the location of the sampled sections [7], which provided a total of 57 samples. The Formigoso Formation was sampled in Ensenada de Llumeres (point 1, fig. 1) and in Clavillas (point 2, fig. 1). The Pizarras del Sueve Formation was sampled in the typical locality (section of Pico Pienzu, point 3, fig. 1, see [10]) and at Collado de Peñamayor (point 4, fig. 1). The Paquete Fresnedo was also checked in two sections (Rioseco and Felechosa, points 5 and 6, fig. 1), and the San Emiliano Formation in the section of Casares de Arbás (province of León, point 7, fig. 1).

Figure 2 shows the field aspects of the sampled rocks.
Materials and methodology

A description is now given of the materials used and methods followed in each one of the various studies that had to be carried out:

1. Polarised Optical Microscopy (POM). Whenever possible (51 out of the 57 samples), thin sample sheets were prepared for examination under a Leica DMLP petrographic polarisation microscope, in transmission mode, to determine the mineralogy and texture and then classify each one of the samples. Some polished sections were also analysed with the same equipment, this time in reflection mode.

2. X-ray diffraction (XRD). This technique was used as a complement to optical microscopy to identify mineral phases with such a small grain size (under 2 μm) that they could not be identified by the latter procedure. For this reason the powder XRD method was used in all cases (18 samples) and a Philips X'Pert Pro powder diffractometer fitted with a copper anode tube.

3. Scanning electron microscopy. Due to its power of resolution and its electronic image-formation procedures, this technique is particularly suitable for the study of mineral phases and textures of a very small grain size, especially mineral inclusions. The equipment used was a JEOL JSM 5600 scanning electron microscope using secondary and back-scattered electrons and a secondary-electron image resolution, in High-Vac mode, of up to 3.5 nm (300,000 times magnification).

4. X-ray fluorescence (XRF). The geochemical analysis of the inorganic sample fraction was carried out by X-ray fluorescence (XRF) on a variable amount of subsample (about 10-20 grams, previously dried and ground in a ring mill) on the whole set of 57 samples. Two XRF analysers were used for this purpose, Niton's Xlt3 and Oxford’s X-MET 3000 TXS+. Both analysers have copper anode X ray tubes (maximum working voltages of 50 and 40 kV, respectively). The approximate measuring time in all cases was 180 seconds.

5. Total organic carbon (TOC) content. This was conducted on a subsample (~ 1 g) of each one of the 57 original samples, determining the sample’s content in total carbon (TC) and inorganic carbon (IC), then obtaining the difference between both readings. The readings were taken by a Shimadzu Total Organic Carbon analyser TOCV SSM-5000A.

6. Vitrinite reflectance. Vitrinite reflectance readings (vitrinite is one of the coal macerals) is one of the commonest coal ranking procedures. This parameter is bound up with the degree of aromaticity of the components and, ipso facto, their maturation. These analyses were conducted in Weatherford Labs in Houston (Texas, USA), following the procedure detailed in ASTM D2798-09a (equivalent to ISO 7404).

7. Whole-rock pyrolysis (Rock-Eval test). This test, involving controlled heating (whole-rock pyrolysis) in an inert atmosphere (usually of He, up to 550 °C), is commonly used for oil and gas exploration, since it gives information on the tested sample’s potential as hydrocarbon source rock (~100 mg). These readings were taken in the same laboratory as the vitrinite reflectance test.

8. The instrumental techniques detailed in points A, B and C are applied to find out the sample’s mineralogical and textural properties and pore spectrum. This result is especially important in terms of its storage behaviour, whether to assess how far the gas it might contain would be recoverable [12] or to ascertain its CO₂ sequestration capacity. For its part, technique D establishes the inorganic geochemistry of the samples; this then serves as the basis for estimating the organic matter’s hydrocarbon production capacity (in particular the Fe/S and Ni/Ni+V ratios). Finally, techniques E, F and G are bound up mostly with the first of the proposed objectives, allowing us to ascertain the amount of organic matter, its degree of maturation and the amount and type of hydrocarbon that might be generated.
Table 1. Summary of the results of the various studies carried out on the samples.

<table>
<thead>
<tr>
<th>Rock</th>
<th>Formigoso Formation</th>
<th>Sueve Formation</th>
<th>Fresnedo Formation</th>
<th>San Emiliano Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>Lutite</td>
<td>Lutite</td>
<td>Lutite</td>
<td>Lutite</td>
</tr>
<tr>
<td>Voids (%m visible) (mean)</td>
<td>0-4,5 (2,39)</td>
<td>1-26 (7,66)</td>
<td>0-5 (2,09)</td>
<td>1-4 (2,06)</td>
</tr>
<tr>
<td>Inorganic geochemistry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major elements</td>
<td>Si, O, Fe, K</td>
<td>Si, O, Fe, K</td>
<td>Si, O, Fe, K</td>
<td>Si, O, Fe, ?K</td>
</tr>
<tr>
<td>Minor elements</td>
<td>Ti, S (Zr)</td>
<td>Ti, Mn, Ca</td>
<td>Ti, S (Mn)</td>
<td>Ti, Ca (Mn)</td>
</tr>
<tr>
<td>TOC (o)</td>
<td>Max. 1.23</td>
<td>0.75</td>
<td>2.08</td>
<td>5.71</td>
</tr>
<tr>
<td></td>
<td>Min. 0.15</td>
<td>0.1</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Mean 0.576</td>
<td>0.31</td>
<td>0.67</td>
<td>1.01</td>
</tr>
<tr>
<td>Ro (%)</td>
<td>Max. 1.31</td>
<td>1.79</td>
<td>1.31</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Min. 0.89</td>
<td>1.60</td>
<td>0.90</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Mean 1.09</td>
<td>1.69</td>
<td>1.07</td>
<td>0.66</td>
</tr>
<tr>
<td>Kerógeno</td>
<td>Amorphous MO</td>
<td>Liptinite</td>
<td>Liptinite</td>
<td>Vitrinite</td>
</tr>
<tr>
<td>Rock-Eval</td>
<td>S1 0.03</td>
<td>0.04</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>S2 0.06</td>
<td>0.05</td>
<td>0.07</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>S3 1.35</td>
<td>0.54</td>
<td>0.78</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>T_{Max.} 489</td>
<td>433</td>
<td>506</td>
<td>459</td>
</tr>
</tbody>
</table>

Results

Table 1 shows the results of the tests carried out on the field samples. The symbols of the mineralogy row stand for the following: Q (quartz), Mus (muscovite), RF (rock fragments), Op (opaque minerals), Cli (clinochlore), Ill (illite), Dick (dickite), Pyr (pyrophyllite) y kaol (kaolinite). S1 and S2 are expressed in mg HC/g of rock, S3 in mg CO2/g of rock and T_{Max} in °C.

The organic carbon content of the Formigoso, San Emiliano and Paquete Fresnedo formations makes them, a priori, promising in terms of natural gas generation.

Figures 3 and 4 show some representative images of sample mineralogy and texture, the first taken with polarised optical microscopy and the second with scanning electron microscopy.
The microscopy results (POM and SEM) are unequivocal: they confirm that the sample rocks are predominantly lutites (sensu stricto), that there are no clear signs of metamorphism in any of the cases and that the fundamental mineralogy is quartz and muscovite, plus some other phyllosilicates in moderate quantities.

X-ray techniques show the presence of clinochlore in the matrix (moderate cation exchange capacity for a phyllosilicate, 10-40 meq/100g); furthermore, associated minor elements always include Ti and, in some cases, S, Mn, Ca and Zr. In any case none of the abovementioned aspects represent anything unusual for lutite rocks. The content of S, Ni and V often falls below the detection limit or comes out as a score or so of mg/kg, so it would not be reliable to make any interpretations about the Fe/S or Ni/(Ni+V) ratios.
The porosity (voids) of this type of rock is closely bound up with open microfractures: those bigger than 1 μm added up to about 2% of total rock volume.

Total organic carbon (TOC) analyses were conducted for all 57 samples, the readings varying from 0.1% to 5.71% in weight, most falling within the interval 0.5 to 1%. According to the data shown in table 1, the Pizarras del Sueve formation is the only rock that, on average, does not record the minimum threshold that would make it worthwhile for hydrocarbon generating purposes (0.5% in weight of organic carbon [14]). The hydrocarbon-generation potential of the Formigoso and Paquete Fresnedo formations would be moderate (0.5-0.7%), while that of the San Emilian formation falls on the good-moderate border (1%).

The rest of the specific analyses to establish the properties of organic matter were conducted on four samples, the ones showing the highest TOC reading of all those studied. As already pointed out, ranking was determined by vitrinite reflectance. Readings are now given for each rock and the relation with kerogen constituents:

- **Formigoso formation.** The dominant organic matter, scarce in any case, is the non fluorescent amorphous type (amorphinite). The particles of the type of vitrinite (="pseudo-vitrinite="), given that the rock dates from the Silurian period; as such it cannot contain vitrinite) are very small. On the basis of seven readings on the bigger particles, the mean reflectance of pseudo-vitrinite is 1.09%. Under transmitted light the predominant organic matter is amorphous, brown in colour, indicating a TAI (Thermal Alteration Index) of 3. The pollen and spores also show up as brown, this colour chiming in with a vitrinite reflectance of -1.1%. The reflectance readings and colour of the palynomorphs show that the organic matter falls within the wet gas window.

- **Pizarras del Sueve formation.** Kerogen is dominated by low quality non-fluorescent amorphous matter. Also present were carbonaceous particles and algal material (post mature) in moderate quantities. The TAI would therefore come out at close to 4, based on brownish monolete spores. The kerogen is classified as type II, with a medium-low gaseous hydrocarbon generation potential. Vitrinite reflectance shows the kerogen to be mature and in the wet gas window.

- **Paquete Fresnedo.** The vitrinite is predominantly organic matter. Inertinite is also frequent and is represented by inertodetrinite. The amorphous organic matter is granular and, on occasions, weakly fluorescent. Based on 50 readings, the mean vitrinite reflectance is 1.07%. The amorphous organic matter is brown, suggesting a TAI of 3. Pollen and spores are also brown and their colour tallies with a vitrinite reflectance of -1.1%, close to the mean value. The vitrinite reflectance values and the colour of the palynomorphs show that the organic matter falls within the wet gas window.

- **San Emilian formation.** Vitrinite is the dominant type of organic matter. Inertinite is less frequent and is represented by inertodetrinite. The amorphous organic matter is granular with a light-brown-hued fluorescence. Based on 50 readings, the mean vitrinite reflectance is 0.66%. The amorphous organic matter is a yellowish brown colour, indicating a TAI of 2.5. The pollen and spores are amber coloured, corresponding to a vitrinite reflectance of -0.65%, similar to the mean value. The vitrinite reflectance values and the palynomorph colour show that the organic matter is in an early maturity state within the oil generation window.

Finally, the whole-rock pyrolysis test tells us the type of kerogen, the hydrocarbon-generation capacity and maturity, basically in terms of four parameters: S1, S2, S3 and Tmax (see table 1). As in the case of TOC, a direct estimate can be made of the hydrocarbon-generation potential from the value of S1 and S2, as shown in table 2.

The type of hydrocarbon generated can be estimated from the hydrogen index (HI), defined as HI=(S2 x 100)/TOC, and the reference values as shown in table 3.

### Table 2: Potential as source rock in terms of the S1 and S2 values[13].

<table>
<thead>
<tr>
<th>S1 (mg HC/g rock)</th>
<th>S2 (mg HC/g rock)</th>
<th>Hydrocarbon generation potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0,5</td>
<td>&lt;2,5</td>
<td>Poor</td>
</tr>
<tr>
<td>0,5-1</td>
<td>2,5-5</td>
<td>Moderate</td>
</tr>
<tr>
<td>1-2</td>
<td>5-10</td>
<td>Good</td>
</tr>
<tr>
<td>&gt;2</td>
<td>&gt;10</td>
<td>Very good</td>
</tr>
</tbody>
</table>


Table 3. Type of hydrocarbon generated in terms of the HI and S2/S3 values [13].

<table>
<thead>
<tr>
<th>HI (mg HC/g Corg)</th>
<th>S2/S3</th>
<th>Type of hydrocarbon generated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-150</td>
<td>0-3</td>
<td>Gas</td>
</tr>
<tr>
<td>150-300</td>
<td>3-5</td>
<td>Oil and gas</td>
</tr>
<tr>
<td>&gt;300</td>
<td>&gt;5</td>
<td>Oil</td>
</tr>
</tbody>
</table>

The Rock-Eval test results are discussed below for each rock type in turn:

- **Formigoso formation.** The S1 and S2 values are very low, not adding up to 0.1 between them, so the source rock potential of the Formigoso formation would be dubious. Consideration must also be given here, however, to the fact that the samples were taken from outcrops, so these findings need to be borne out with unaltered rock massif samples. The HI value (5) confirms that the hydrocarbon generated would be natural gas. Tmax is not valid since S2 is lower than 0.2. The type of kerogen, by visual analysis, is mainly amorphous organic matter, more habitual in oil source rocks.

- **Pizarras del Sueve formation.** The S1 and S2 readings are very similar to those of Formigoso formation, so the same considerations apply. Likewise the value of HI (7) confirms that the hydrocarbon generated would be natural gas. Tmax is again invalid for establishing the rank.

- **Paquete Fresnedo.** The S2 value, albeit somewhat higher than for the Formigoso and Pizarras del Sueve formations, is also too low to validate the calculated data for Tmax. The sum of S1 and S2 would not qualify Paquete Fresnedo as source rock (see similar comments for the Formigoso formation). Once more the HI value (3) confirms that natural gas would be the hydrocarbon generated.

- **San Emiliano formation.** Vitrinite, as already pointed out, shows a reflectance corresponding to the oil generation window (0.66%), in an early state of maturation. S2, in this case, presents a value that validates the calculated Tmax and is the highest of all, although the sum of S1 and S2 does not, a priori, suggest a suitable source rock (see comments made for the Formigoso formation). The HI value (9), however, indicates natural-gas generation potential rather than oil.

**Conclusions**

The degree of maturation of the organic matter contained in the rocks shows that the Formigoso, Pizarras del Sueve and Paquete Fresnedo formations could generate natural gas, while the San Emiliano formation would have oil-generation potential.

The first conclusions to be drawn from this work concern the potential of each of the studied rocks as worthwhile unconventional natural gas sources:

- The fundamental mineralogy of these rocks is very similar in all cases: quartz, muscovite and opaque minerals as grains (to a lesser degree, zircon and rock fragments) and, as matrix, quartz again (sometimes chert), clinohlore.

- They are also fairly similar from the organic geochemical point of view, with Fe (3-5%), K (2-3%), Si and O as the main elements (perhaps also Al and Mg, which could not be determined due to limitations of the techniques used). Minor elements include Ti (0.5-1%) and, on occasion, some others (S>Ca>Mn>Zr).

- Total organic carbon readings range from 0.31% of the Pizarras del Sueve formation to 1.01% of the San Emiliano formation, with intermediate values for the Formigoso and Paquete Fresnedo formations (0.57% and 0.67%, respectively). Considering exclusively this last factor, the prospects of serving as hydrocarbon generating source rock would be good or moderate for the San Emiliano formation, moderate for Paquete Fresnedo and Formigoso and poor for Pizarras del Sueve.

- In the four cases their potential as source rock is limited and always for natural gas, barring the San Emiliano formation. In no case does the Rock-Eval pyrolysis reading reach the established threshold for hydrocarbon source rock (S1+S2>0.2). In all cases both S1 and S2 are less than 0.1, except for S2 in the San Emiliano formation (0.54). S1 and S2 readings, taken from outcrops, may well not reflect the true underlying situation of the bedrock.

- The calculated rank parameters (vitrinite reflectance, TAI) situate the Formigoso formation and Paquete Fresnedo in the early states of the wet gas window, the Pizarras del Sueve formation in the middle of the wet gas window and the San Emiliano formation in the oil generation window.
• Looking at future priorities for natural gas exploration, the San Emiliano formation can be ruled out as insufficiently mature. Of the remaining three, which do lie in the wet gas window, the best possibilities are presented by Paquete Fresnedo, for three main reasons: a) it is the thickest of the three and hence is most likely to have the best reserves; b) the TOC is appreciably higher than those of the Formigoso and Pizarras del Sueve formations; and c) the S2 value is significantly higher than for the other rocks.

In light of the data obtained, future work should focus on the Paquete Fresnedo formation, a succession almost 500 m thick appearing on the eastern border of the central Asturian basin.

As for their potential for future geological CO₂ sequestration, the following factors have to be taken into account:

• The percentage of voids bigger than 1 μm (intergranular and due to open fracturing, much commoner) is similar (2 to 2.5%) for the formations Formigoso, San Emiliano and Paquete Fresnedo. The Pizarras del Sueve formation shows much higher values, coming out as 7.66% on average. The SEM images show very rugged rocks at micrometric observation scale and with many voids not identifiable with optical microscopy and therefore not quantified in earlier data.

• Simple geometric considerations show that all of them reach suitable depths relatively close to their respective outcrop areas (over 800 metres).

• As regards the formations Formigoso, Pizarras del Sueve and Paquete Fresnedo, the CO₂ that might be sequestered there would come mainly from the centre of the region, where there are several thermal power plants and two cement plants. Bearing in mind such salient factors as the thickness of each one, their proximity to the emitting sources and the fact that organic matter would play the role of absorbent, it is the Paquete Fresnedo that once more comes across as the best option.

• For the Paquete Fresnedo the most suitable area would be that lying between the Sierra de Peñamayor and El Condado (Laviana), with a mean westwards dip. According to structural data the Paquete Fresnedo would attain the depth of 800 to 900 metres westwards of the zone of contact with the overlying rock (Caliza de Peñarredonda formation). The San Emiliano formation, along the same lines as in the above paragraph, would be a possible candidate for sequestering emissions from the La Robla thermal power plant, lying 15 kilometres (minimum distance) from the nearest outcrop. It is the thickest formation with the most clayey texture and also the richest in organic matter. Apart from transport considerations, therefore, it would be the best option, though it does lie vertically in the study zone and this could prove a handicap.

ACKNOWLEDGEMENTS

The sampling and analysis part of this work was funded exclusively by FUNDACIÓN MAPFRE through its research aids programme. This work was originally the brainchild of Dr. Fernando Pendás (ETS de Ingenieros de Minas de Oviedo). The work as presented herein has then been enriched with further contributions from Dr. Julio Riba (Departamento de Ciencia de los Materiales e Ingeniería Metalúrgica) and Dr. Carlos Aramburu (Departamento de Geología), both from Universidad de Oviedo. Our heartfelt thanks go to all of them.

BY WAY OF A GLOSSARY

Geological CO₂ sequestration. This involves the injection of CO₂ as a supercritical fluid (so that it behaves as a liquid) into the spectrum of pores and fractures of a rock so that it remains sequestered there safely for a long period of time.

Shale Gas. Natural gas recovered from very fine-grain sedimentary rock made up by quartz and clayey minerals with a certain organic matter content of sufficient maturation for gas generation.

Inertinite. One of the components (organic component) of the carbonaceous matter formed by the remains of vegetal tissues, previously oxidised and/or altered.

Kerogen. Organic matter fraction insoluble in benzene and other common organic solvents.

Lutite. Fine- to very-fine grained detrital sedimentary rock of which over 75% of its constituents have a grain size of less than 30 microns.

Palynomorphs. Continental palynomorphs, made up by pollen, spores and remains of freshwater algae, are those of interest for hydrocarbon exploration purposes.
Reflectance (or reflectivity). Light fraction (polarised or not) reflected by a mineral or maceral, with respect to a known pattern and under standard lighting conditions. It is expressed as a percentage.

TAI (Thermal Alteration Index). A number scale 1 to 5 for estimating the rank (degree of maturation) of organic matter according to the colour of the pollen and spore remains by comparison with a standard card. It is correlated with vitrinite reflectance.

«Gas window». Interval of vitrinite reflectance values corresponding to the maturation states of organic matter in which the latter is capable of generating natural gas. Usually represented in a Dow diagram.

«Oil window». See above definition, replacing «natural gas» by «oil».

Vitrinite. Another of the components (organic constituent) of carbonaceous matter formed by remains of vegetal tissues, buried in fresh state or little altered. It is the prime component of most humic coal.

TO FIND OUT MORE


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