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A 3D geological model for a potential CO_2 reservoir in the El Bierzo Basin (Carboniferous, NW Spain)

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ABSTRACT

A 3D geological model of the Torre-Bembibre Carboniferous sub-basin, a potential CO_2 storage reservoir, is proposed here. The Torre-Bembibre sub-basin is part of the El Bierzo coal-bearing Carboniferous basin located in the westernmost part of León province (NW Spain). It covers an area of about 150 km^2. Carboniferous deposits (up to 1500 m of continental siliciclastics) are divided into nine intervals, defined by earlier coal exploration work. They were deposited as intramontane basin infill within a transpressional regime during the last stages of the Variscan Orogeny and are partially covered by Neogene and Quaternary continental siliciclastic sediments, formed by alluvial plains, fans and terraces. To resolve a 3D geological model of the Torre-Bembibre sub-basin, including outcropping layers and their prolongation at depth, a 3D dip-domain method was applied, where data from all stratigraphic positions were used to compose a coherent geological reconstruction of the stratigraphic surfaces. Subsurface information was available from previous and newly acquired seismic reflection profiles and boreholes. The 3D model helped resolving some uncertainties, specifically: (i) the western termination of the Carboniferous basin under the Tertiary sediments, corresponding to an NNE–SSW normal fault, (ii) the depth and morphology of the base of the Carboniferous strata and (iii) the morphology of the intra-Carboniferous layers. The syncline/anticline shape of the Torre-Bembibre sub-basin suggests a reservoir which may be capable of storing CO_2 under the Tertiary cover. The total estimated volume is 6.4 km^3, while the total capacity for CO_2 storage could be as much as 7 Mt. The reservoir is most likely located within the major massive sandstone bodies in the Chuchu interval, in the syncline–anticline structure north of the town of Bembibre. The potential capacity of the reservoir calls for undertaking further studies using the proposed 3D geological model in order to determine more precisely the petrophysics and geometry near Bembibre.

Key words: 3D modelling, CO_2 reservoir, NW Iberia, intramontane Bierzo Basin.

INTRODUCTION

The mitigation of greenhouse gas emissions, in particular CO_2, is a main concern in the context of climate change. Carbon dioxide capture and storage could play a key role to meet the ambitious goals set by the European Union. Indeed, the European Commission urges joint efforts in this direction to reduce CO_2 emissions in sectors that make intensive use of fossil fuels.

Since 2009, the Spanish Geological Survey (IGME) has been developing a long-term project called ‘Plan for

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selection and characterization of suitable structures of CO_2 geological storage' (IGME 2009). The first stage of this plan consists of evaluating and pre-selecting a number of areas whose local geological structures might feature closures that make them suitable for CO_2 storage. In addition to gauging the potential storage capacity based on preliminary calculations, the cost of developing the infrastructures was appraised. As a first result of this study, 103 geological structures were selected in Spain with the following distribution: The Betics Cordillera and Guadalquivir basin, 19 structures; Iberian Cordillera, Tajo basin and Almazán basin, 31 structures; Cantabrian Cordillera and Duero basin, 34 structures; and Pyrenees and Ebro basin, 19 structures. The capacity of CO_2 storage was estimated to range between 1 Mt CO_2 and 3 Gt CO_2. The sites were ranked applying standards of favorability/reliability, giving a final number of 55 sites with capacity over 50 Mt of CO_2, located in the regions of Aragón, Castilla y León, Castilla-La Mancha, Comunidad Valenciana-Murcia and Madrid (García Lobón *et al.* 2010). For this first stage, seismic profiles and deep drillholes from the oil exploration were compiled, converted into digital format, and reinterpreted. The second stage of this plan calls for completing detailed studies of the selected structures to obtain a more precise image of the structural closures that might serve as reservoirs and more accurately assess their storage capacity. Although the Torre-Bembibre sub-basin does not have a particularly high capacity, it lends itself to 3D geological model reconstructions of outcropping geology and subsurface information, and the acquisition of a new seismic profile. Northwest Spain has a high concentration of coal-bearing basins and power plants. In El Bierzo, where the coal mines are now closed, two power plants continue to function. One of them, Compostilla (1340 Mw), is less than 20 km away from the Torre-Bembibre sub-basin. For this reason, we chose it to investigate whether the reservoir seal or coal levels make the Torre sub-basin a potential CO_2 reservoir with favourable structure, burial and seal conditions. In fact, only sedimentary basins contain geological media that are generally suitable for CO_2 storage and/or sequestration: oil and gas reservoirs (geological and solubility trapping), deep sandstone and carbonate aquifers (solubility, hydrodynamic and mineral trapping), coal beds (adsorption storage and trapping), and salt beds and domes (cavern trapping) (Bachu 2003).

GEOLOGICAL SETTING

The El Bierzo Carboniferous intramontane basin lies over the previously folded and faulted Lower Paleozoic West Asturian-Leonese Zone (WALZ; Lotze 1945) of Iberia (Fig. 1a). It is a coal-bearing intramontane basin that opened in a transpressive setting during the last pulses of the Variscan (Hercynian) Orogeny.

Located near the northern edge of the Iberian microplate (Fig. 1a) – within the Astur-Galaica Region (AGR) *sensu* Martín-González and Heredia (2008) – El Bierzo basin was also affected by Alpine (Pyrenean) Orogeny during the Tertiary, forming a pop-down structure between the Cantabrian Mountains to the north and the Galaico-Leonese Mountains to the south (Martín-González and Heredia 2011). The AGR is characterized by an absence of Mesozoic sediments and a thick-skinned tectonic style, that is, without detachment between the cover and the basement (Martín-González and Heredia 2008). According to the model proposed by these authors, the Neogene sediments that partially overlie the Carboniferous basin and the WALZ basement were deposited as part of the Duero basin, the foreland basin of the Cantabrian Mountains.

The Tertiary basin infill is made up of red-orange continental siliciclastic sediments, mainly fine-grained, with sandy decimetric beds and some gravel lenticular beds, all corresponding to the Toral (Late Eocene-Oligocene) and Santolalla (Oligocene–Early Miocene) Formations described by Herail (1981). Sand clasts are mainly lithic (Paleozoic shale fragments) and secondarily quartz, while gravels are mainly quartzitic. Illite is the predominant clay mineral (Velando and Martínez 1972). The lower Toral Formation pertains to an alluvial plain to distal alluvial fan depositional environment; the upper Santolalla Fm shows a proximal alluvial character. Both were deposited in an arid or semi-arid environment crossed by fluvial channels from the surrounding ranges to the north (Cantabrian Mountains) and south (Galaico-Leonese Mountains) according to the paleocurrent data reported by Martín-González and Heredia (2008). The lower mostly fine-grained formation transitions to the upper formation, where a greater presence of coarse-grained beds shows an upward-coarsening sequence.

El Bierzo basin, crossed by some important faults (Fig. 1a), is divided into several sub-basins. This work focuses on the southernmost one, the Torre-Bembibre sub-basin. It is compartmentalized by a family of E–W trending thrust faults and N–S trending normal and/or strike slip faults (Fig. 1b). Carboniferous outcrops occur only in the southern and eastern parts of the study area, while the Carboniferous is overlain by Tertiary and Quaternary sediments in the central part of the basin and its northern and western limits (Fig. 1b).

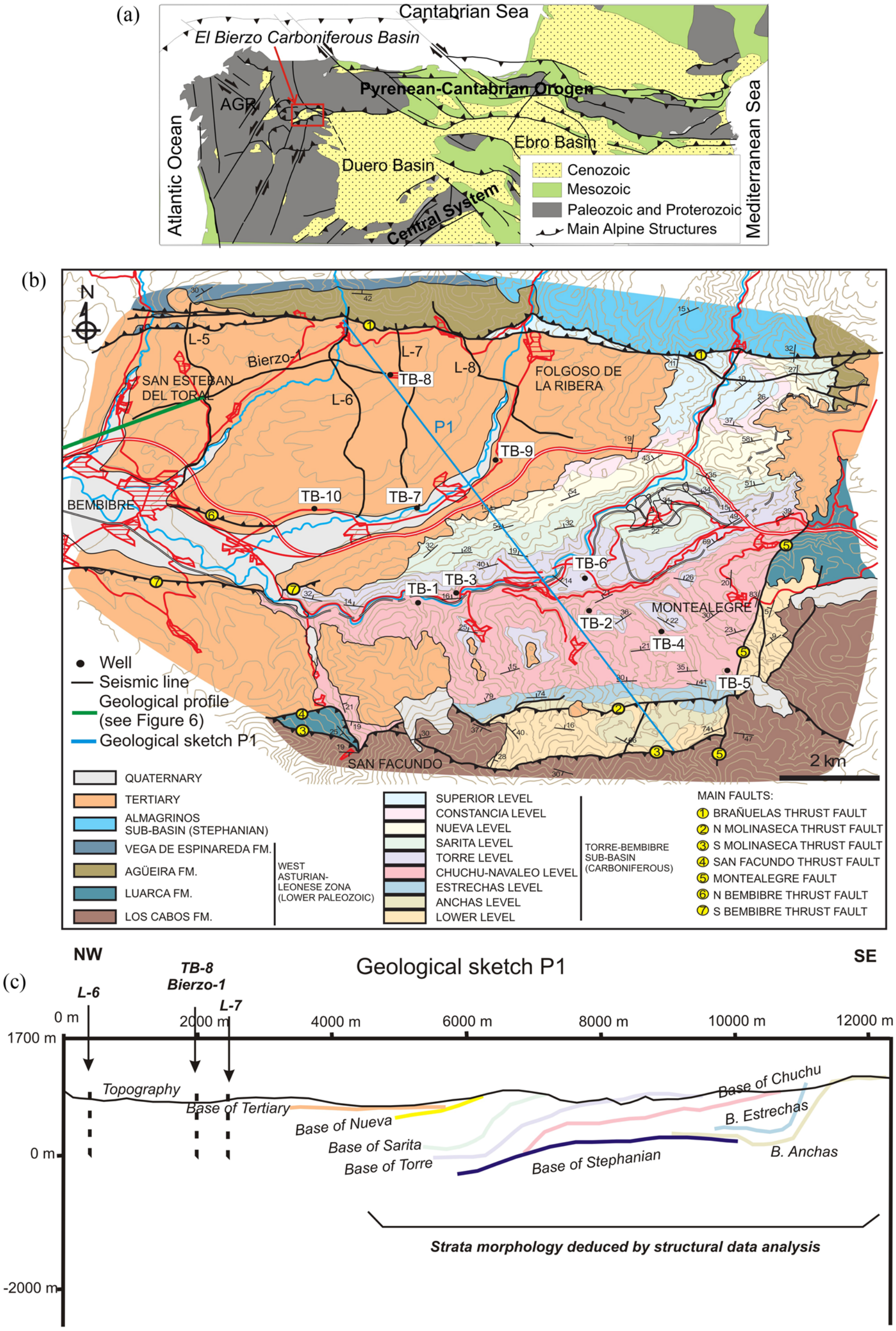

Figure 1 (a) Generalized geological map of the Alpine Pyrenean-Cantabrian Orogen along the northern Iberian Peninsula, showing the main Alpine structures and foreland basins. AGR: Astur-Galaica Region. The red rectangle highlights the location of the El Bierzo Carboniferous Basin. (b) Geological map of the Torre-Bembibre sub-basin, where Paleozoic formations and Carboniferous detailed stratigraphy are shown. The position of the seismic lines (black lines), geological profile (in green), geological sketch P1 (in blue) and the wells (black dots) are also depicted. (c) NW–SE geological sketch P1 across the Torre-Bembibre sub-basin deduced from field data. The northern part of the profile lacks subsurface information.

3D MODELLING OF THE TORRE-BEMBIBRE SUB-BASIN

In the Torre-Bembibre sub-basin, Carboniferous strata comprise up to 1500 m of continental siliciclastics and are divided into nine intervals based on historical coal mining exploration and extraction data (Fig. 1b). These stratigraphic strata are (from base to top): Lower, Anchas, Estrechas, Chuchu-Navaleo, Torre, Sarita, Nueva, Constancia and Superior Units, most named after key coal-bearing intervals. Despite the formerly extensive coal extraction in the area, data are scarce, and there was no general geological model for the Torre-Bembibre sub-basin prior to this study.

Carboniferous strata were deposited in the El Bierzo intramontane basin within a transpressive regime during the last phases of the Variscan Orogeny. Later, during the Alpine Orogeny, E–W trending faults were reactivated as thrust faults inducing local tectonic inversion. The main thrusts are the Brañuelas north-dipping Thrust Fault located along the northern border of the basin (1 in Fig. 1b), and the Molinaseca and San Facundo south-dipping thrust faults (2, 3 and 4 in Fig. 1b). Some of the N–S strike faults (e.g. Montealegre normal fault, 5 in Fig. 1b) were not reactivated or formed tear faults of E–W trending thrusts, later covered by Tertiary sediments. Some intra-basin faults were also present during the initial Carboniferous basin configuration (e.g. South Bembibre thrust fault, allowing the Lower Paleozoic to crop out south of the town of Bembibre, 7 in Fig. 1b). The map in Fig. 1b was originally presented by Motis and Rey-Moral (2008) in an early stage of the present work; though earlier maps are of high quality, this is the first detailed work showing the motion character and the timing of the main structures in the basin area.

The final geological 3D reconstruction presented in this work involves 10 stratigraphic surfaces. The geological surfaces do not preserve a constant geometry (there are channel-shaped erosive surfaces, facies changes, minor faults and folds presence, and so on). Such complexity, with changes in the dip distribution and the thickness of the strata, increases the uncertainty of the model. This drawback could be minimized if a good set of geophysical data were available, especially where the Carboniferous strata do not crop out. Direct field structural data are available in the eastern–southeastern area, whereas in the northern–central part of the basin they must be extrapolated, as it is overlain by Tertiary and Quaternary sediments. The available subsurface data for Torre-Bembibre sub-basin included information from 32 exploration wells (most of them drilling the southeastern area, rarely in the Tertiary basin), and four former seismic profiles over the Tertiary and Quaternary cover (see location in Fig. 1b).

METHODOLOGY

Geological data are not continuous but spotty and restricted only to existing and accessible outcrops. Therefore, data sets must be interpolated, estimated or simulated when building a 3D geological model. In order to solve that, different methods have been proposed to generate the 3D reconstructions of geological bodies and structures.

The method that we have applied was originally developed by Fernández *et al.* (2004). These authors developed a method based on the ‘dip-domain’ concept, where every geological structure can be discretized in constant dip and azimuth volumes with bisector surfaces joining them, creating objects with a geological meaning. The method can be applied to individual irregular surfaces if structural data are available for that surface.

From each known point (defined by x, y, z, dip and azimuth), a horizon can be reconstructed extending it laterally according to the geometry of the dip domain. The result is an area with the same dip and azimuth as the central point (hard data). The size of this area depends on the amount of structural information available and the expertise of the geologist evaluating the structural style.

To build the best possible 3D model, the horizon reconstruction process requires a vast amount of data. However, not all the available data necessarily lie on the horizon under reconstruction. In other words, there is generally a stratigraphic distance between a given point and the reference horizon to be reconstructed. The 3D geometric dip domain and the stratigraphic layout establish a framework. According to that framework, each data point can be projected onto the horizon under reconstruction to constrain its geometry. The knowledge of the stratigraphic separation between the horizon to be reconstructed and every data point in the new dip domain is thus needed to constrain the position of the horizon and, consequently, that of the bounding bisector surface.

In this process, the study area must be subdivided into a set of geo-objects with the goal of compiling all the data related to them in terms of topology, geometry and geological properties. These geo-objects are diverse and can be faulted blocks, horizons, reservoirs, ore bodies and so on. The next step consists of creating self-consistent 3D geological models of geo-objects using interpolation, estimation and simulation. Finally, the geological model must be fitted to the geophysical data.

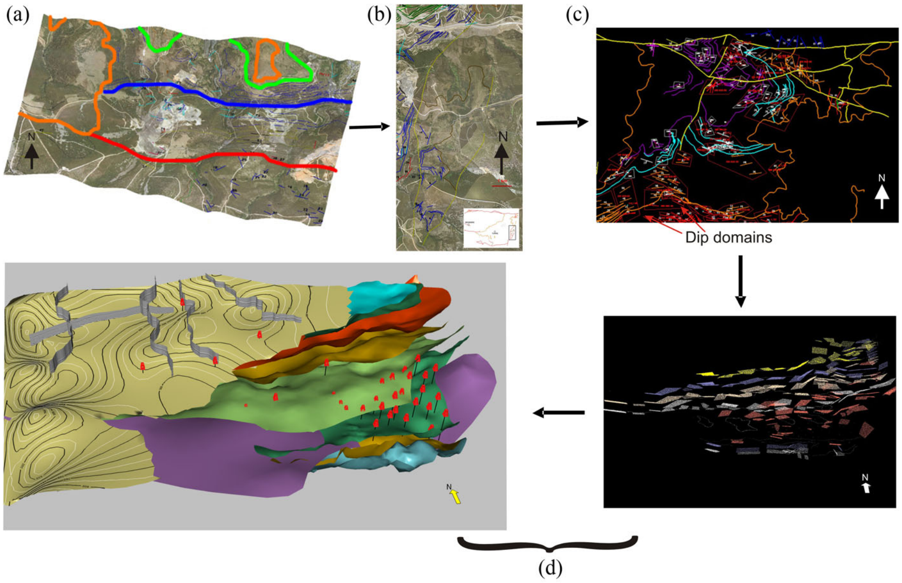

Figure 2 Illustration of selected steps of the reconstruction process. (a) Digitized cartographic traces corresponding to selected strata on a topographic surface extracted from a digital terrain model (DTM) with corresponding orthophoto. (b) 3D georeferenced image, with layer contacts, strata and dips incorporated. (c) Structural analysis in a 3D frame, providing average dip, dip domains, orientation and so on. (d) Point conversion prior to (TIN) surfaces, and final geological model showing the 10 surfaces (view from south), together with the location of the seismic profiles and boreholes.

The surface reconstruction methodology used in this work can be summarized as follows (Fig. 2):

1. All data are gathered and the reference surfaces are chosen. The gathering must include all sorts of data that are available (i.e. surface geology, borehole-derived data and geophysical data). The reference surface is a stratigraphic surface (level, bed, unconformity, and so on) that is easy to identify throughout the area and for which there are enough data points. A 3D reference surface in the model represents the basis for the 3D reconstruction of other surfaces if stratigraphic distances and possible variations among them are known.
2. Field data for the reference surfaces are digitized on a topographic 3D surface in view of a digital terrain model (DTM) with the corresponding orthoimages draped on it (Fig. 2a). The result is a 3D georeferenced image, where contacts, strike and dip, and faults affecting them are represented (Fig. 2b).
3. The geometrical analysis of the surface traces on the DTM representation provides average dip values and orientation for areas that are not easily accessible and helps densify the sampling of structural measures (Fig. 2c).
4. The definition of dip domains and dip-domain boundaries is derived from the analysis of structural data and measurements of the stratigraphic distance (i.e. thickness) between different surfaces (Fig. 2c).
5. 3D structural reference surfaces are generated by projecting data from lower and upper stratigraphic horizons orthogonally to the bedding. The initial data set for the 3D reconstruction is completed in this step.
6. The data set is loaded to a geomodelling software and converted to point sets. The point sets are triangulated to obtain triangulated irregular network (TIN) surfaces (Fig. 2d) that are interpolated using the Discrete Smooth Interpolator (DSI). DSI relies on a triangular mesh with an arbitrary set of nodes fixed by the user (constraints) to assign coordinates to the other nodes of the mesh. Multiple iterations progressively reduce the sharpness of the final surface. This process is not fully automatic since a 'hand-made' isobath map or some geological profiles built under the expert eye of a geologist are useful to incorporate control points before generating 3D surfaces.

The software chosen for the above procedure was Bentley MicroStation in a 3D environment, along with Earth Decision Gocad and accessory utilities (see Fernández *et al.* 2004 for further details).

The 3D reconstruction methodology is well suited to individual irregular surfaces if structural data sets are numerous enough to characterize their geometry. In the actual work area, a detailed unpublished geological map of the Carboniferous outcrops was available. Still, a lack of structural information was a handicap. So several months of intensive field work were undertaken, resulting in a new detailed geological map (Fig. 1b) with more than 600 dip data providing the bedding geometry of every layer with maximum precision (Motis and Rey-Moral 2008). The final surfaces were generated honouring the constrained data (Fig. 2d): fieldwork measurements and the borehole database. The modelled layers are base of the Carboniferous, base of the Anchas, base of the Estrechas, base of the Chuchu-Navaleo, base of the Torre, base of the Sarita, base of the Nueva, base of the Constancia and base of the Superior. The base of Tertiary was later incorporated using borehole and seismic data.

To complete this phase, a NW–SE geological sketch of the area was made (Fig. 1c; see location in Fig. 1b), depicting the base surfaces of some north-dipping layers (Tertiary, Nueva, Sarita, Torre, Chuchu, Estrechas, Anchas and base of Carboniferous). These surfaces were deduced merely through structural data analysis; that is, they represent the former 3D model, restricted to the southeast part of Torre-Bembibre sub-basin. The surfaces further north, beneath the Tertiary cover, could not be modelled without the support of subsurface data.

Then, the resulting surface reconstruction was joined to the geophysical subsurface information. The prolongation at depth of the generated surfaces was improved by (i) interpretation of the previous seismic profiles (L-5, L-6, L-7 and L-8) and (ii) using the newly acquired seismic profile (Bierzo-1). The profile Bierzo-1 covers an unexplored area at the northwestern zone of the Torre-Bembibre sub-basin (see Fig. 1b for location).

SEISMIC DATA

In 1980, more than 20 km of seismic profiles (L-5, L-6, L-7 and L-8; see location in Figs 1b and 2) were acquired by the Compañía General de Geofísica (CGG) using high-resolution vibroseismic equipment (the Mini-Sosie method). The objective was to map the subsurface Carboniferous layer geometry within the framework of coal exploration. The seismic profiles obtained showed some significant reflectors suggesting intra-Carboniferous strata and the base of Tertiary strata. Yet, the position of a Carboniferous Lower-Paleozoic unconformity remained unclear.

In August of 2008, a new reflection seismic profile was acquired (Bierzo-1; Fig. 3) to improve subsurface information about the northwest part of the basin, covered by Tertiary sediments. The location of this profile was planned to cross over the previous seismic profiles in an E–W trend. The field work involved a Geometrics Stravisor NZ seismograph, with 60 channels. The acquisition was made with 20 Hz geophones, at a spacing of 10 m. The seismic source was dynamite (0.4 kg of Goma 2 eco) placed in holes with a diameter of 7 cm and a depth of 3–4 m.

The reflection data were processed in the Geological Department of Oviedo University using GLOBE Claritas software. The processing sequence included trace editing, geometry addition to the headers, amplitude balancing, bandpass filtering, deconvolution, muting, static correction, CDP (Common Depth Point) sorting, velocity analysis, NMO (Normal Move Out) correction and stacking. Post-stack processing included FX deconvolution and IME Stolt migration.

The final stack for the Bierzo-1 profile, shown in Fig. 3, has a fairly good resolution up to 0.5 s TWT in the western part and up to 0.7 s TWT to the east. The upper portion exhibits a constant subhorizontal reflectivity, related to the Tertiary strata, having two different seismic trends. This upper seismic set lies disconformably over a lower folded set (between 0.4 and 0.6 TWT) that defines a gentle anticline in the west (between spontaneous potential (SP) 200 and 600) and a gentle syncline eastwards (between SP 1200 and 2000). This folded reflection package is ascribed to the Carboniferous sediments.

Time to depth conversion relies on an adequate seismic velocity model for the study area. Given the scarcity of geological control points (just three wells near the seismic profiles), a single time/depth conversion table was used for the whole area. This means that some stratigraphic variations may be masked, and interpretations may be somewhat biased. To resolve this problem, two control points were used: wells TB-7 and TB-8. They were correlated with velocity values obtained during the seismic reflection profile measurement (symbols G and R in Fig. 3) for the shallower areas.

The reflectors corresponding to base of Torre, base of Sarita, base of Nueva and base of Tertiary were interpreted with the reference to wells TB-7 and TB-8 (see Figs 1b and 3 for location) and the newly acquired seismic profile Bierzo-1. Further seismic profiles, previously interpreted by Compañia General de Geofísica (CGG) were also used (L-5, L-6, L-7 and L-8). The seismic interpretation achieves (i) intra-Carboniferous levels (from base of Torre to base of Nueva) having a syncline–anticline trend (Fig. 3, profile Bierzo-1) and (ii) reflectors dipping northwards, increasing the thickness of Tertiary and intra-Carboniferous layers (Fig. 3). Since the base of Carboniferous could not be clearly distinguished, it was inferred from information obtained during the 3D geological

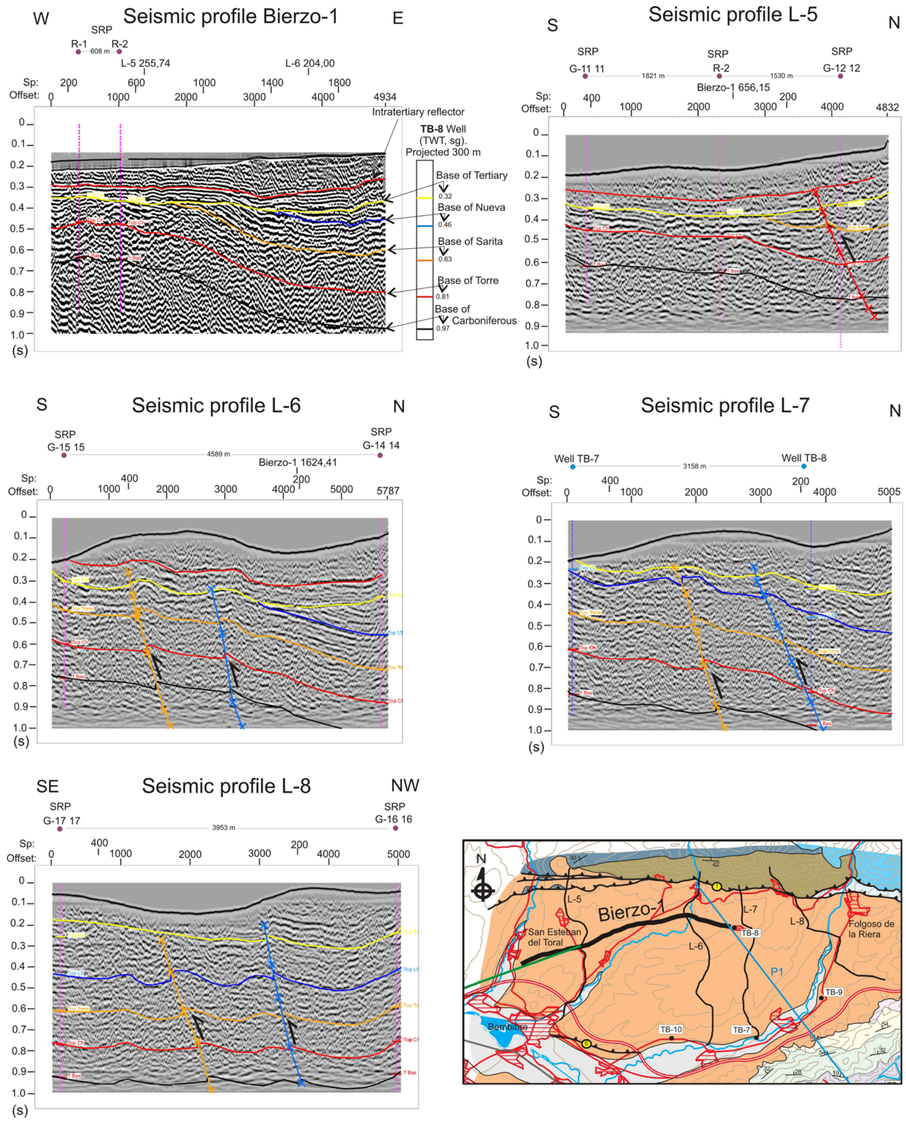

Figure 3 Seismic reflection profiles used in the 3D geological model. Vertical scale in time (s). SP, shot points. SRP: seismic refraction point (G and R). The reflectors interpreted are top of basement (black), base of Carboniferous; top Chuchu (red), base of Torre; top Torre (orange), base of Sarita; top Sarita (blue), base of Nueva; top Estrechas (yellow), base of Tertiary. The uppermost layer in red, in profiles Bierzo-1, L-5 and L-6, corresponds to an intra-Tertiary prominent reflection. TB-7 and TB-8 wells projected as interpretation guidance points.

modelling – layer thickness, pinch outs, structural information – and later included in the seismic profiles. The time/depth conversion table provides an estimation of the depth of the layers.

THE 3D MODEL: TORRE-BEMBIBRE SUB-BASIN GEOMETRY

Figure 4a shows the final 3D geological model, comprising 10 main stratigraphic reference surfaces (base of Carboniferous, eight intra-Carboniferous strata and the Carboniferous-Tertiary boundary) bounded by E–W trending thrust faults and N–S trending faults.

The overall geometry of the basin is defined by the southeast Carboniferous outcropping sediments, determining a syncline geometry, with a westward pinch axis. Under the Tertiary, the morphology and depth of Carboniferous sediments remain uncertain, as does the western limit of the Carboniferous basin. Therefore, the initial model created was enhanced with available subsurface data to build the shapes

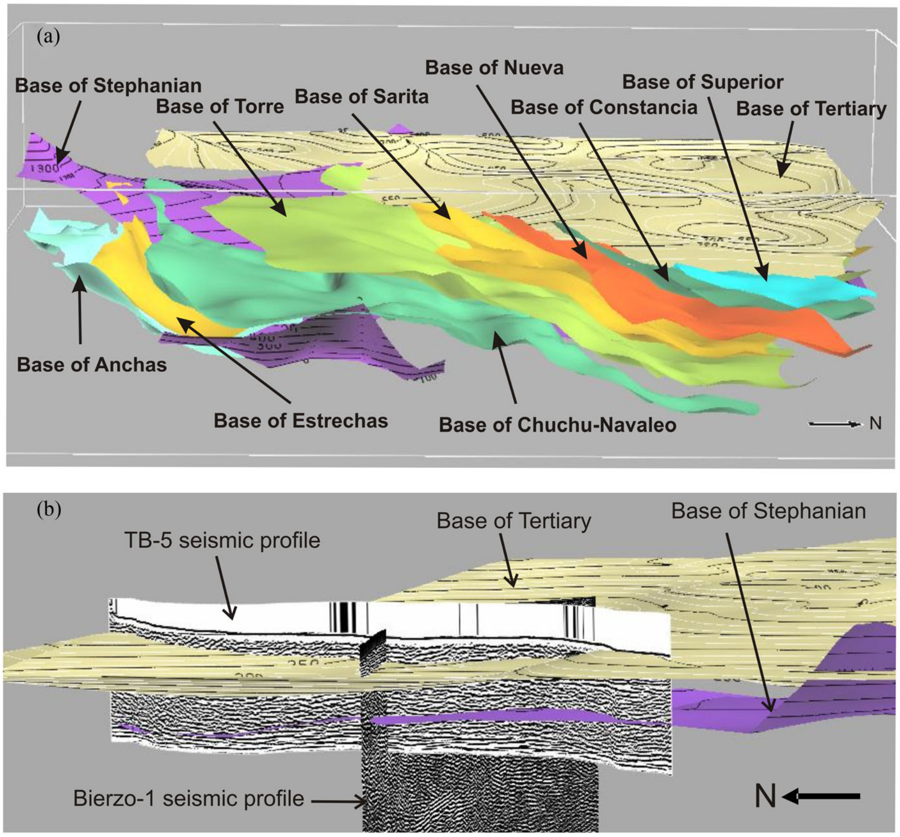

Figure 4 (a) Final 3D geological model of the Torre-Bembibre sub-basin looking from the east showing the 10 modelled surfaces. The intra-Carboniferous layers deepen to the north, adopting a syncline geometry. (b) A composite image of the base of the Tertiary and base of the Carboniferous and the profiles used to infer them, Bierzo-1 and TB-5 looking from the northwest.

under the Cenozoic cover. Geophysical data came from four former seismic reflection profiles (L-5 L-6, L-7, L-8 and the new El Bierzo-1) and the boreholes TB-1, TB-2, TB-3 TB-4, TB-5, TB-6, TB-7, TB-8, TB-9 and TB-10 by Ibérica de Sondeos, S.A. and Compañía General de Sondeos (location in Fig. 1b). The depth of layers deduced from structural data fits well with the interpretation of the five seismic profiles, providing support for interpretation and time/depth conversion. Figure 4b offers a detailed northwestern portion of the 3D geological model. The northward prolongation of the base of Tertiary and base of Carboniferous surfaces is seen to be consistent with the previously interpreted seismic profiles.

The Carboniferous deposits correspond to conglomerates in their lower part, with increasing proportions of shales, sandstones and coal interbedded in the upper terms. As deduced in the 3D geological model, the depth of Carboniferous strata (Fig. 5) increases to the NE, showing a syncline geometry, and reaching over 1500 m deepness under the topographic surface. Towards the west, this surface slightly changes into an anticline, likewise with an N–S trend (Fig. 3, profile Bierzo-1 between SP 200 and 400). Then, it shallows slightly towards the southwest, reaching the top around 800–900 m below the topographic surface in the north block of the South Bembibre thrust fault (Fig. 1b). The lack of subsurface information east of L-8 restricts the interpretation at the eastern part of the basin.

According to the geological map (Fig. 1b), the Anchas and Estrechas surfaces crop out in a narrow area along the southeast limit of the basin. High dip values (Fig. 4a) and the lack of subsurface data make it difficult to extend them downwards; however, borehole data suggest a downlap geometry of all the levels lying under Torre (Fig. 1c). The maximum depth reached by these surfaces is roughly 800 m below the topographic surface.

The base of Chuchu-Navaleo features the anticline–syncline shape mainly deduced from the seismic profiles. It reaches a maximum depth of roughly 1400 m below surface.

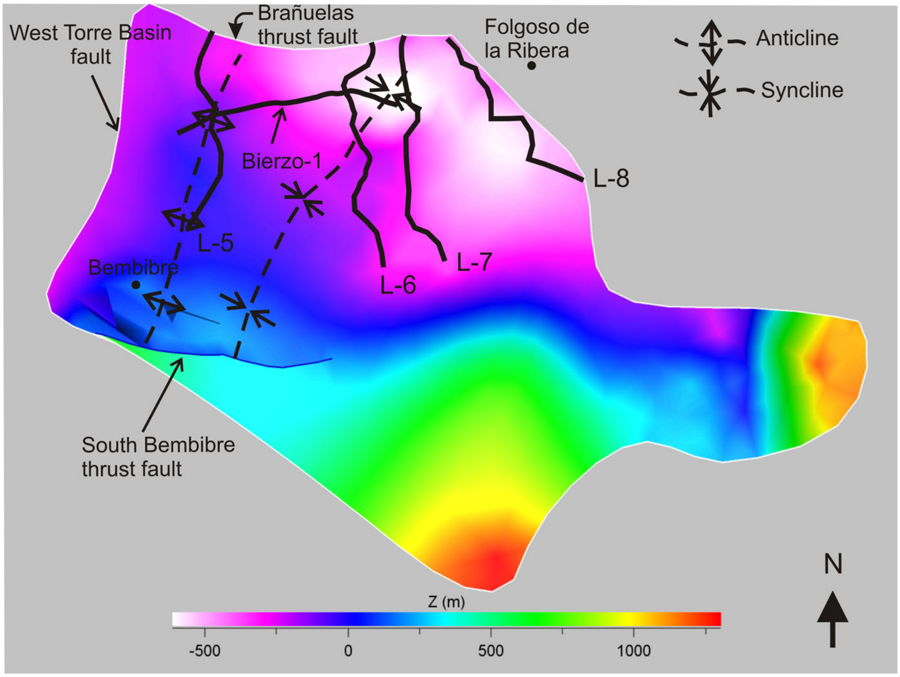

Figure 5 A top view of the base of Carboniferous at depth (referenced to sea level). This surface shows a syncline geometry in the northeast area (pinkish colours), whereas towards the west this surface changes into a gentle anticline maintaining the N–S trend. The structure is framed by the South Bembibre thrust fault, the west Torre Basin fault and the Brañuelas thrust fault to the north.

The Torre, Sarita and Nueva strata crop out in the eastern area of the basin, and their geometry was deduced from field structural data and boreholes. To investigate their prolongation at depth, we use the interpreted seismic profiles. In Fig. 4a, the syncline geometry of these layers is clearly depicted where the depocentre of the base of Torre lies, at a depth of over 1500 m. Sarita level is interpreted to have been eroded westwards under the Tertiary base (Fig. 6).

The bases of Constancia and Superior were inferred from structural data, and hence are restricted to the northeastern margin of the basin (an area not reached by boreholes or the five seismic profiles), where these strata are assumed to be eroded westwards by the Tertiary base. The base of the Tertiary is largely flat, except in the western part of the basin (south of Bembibre town), where a thrust causes the Carboniferous deposits to crop out.

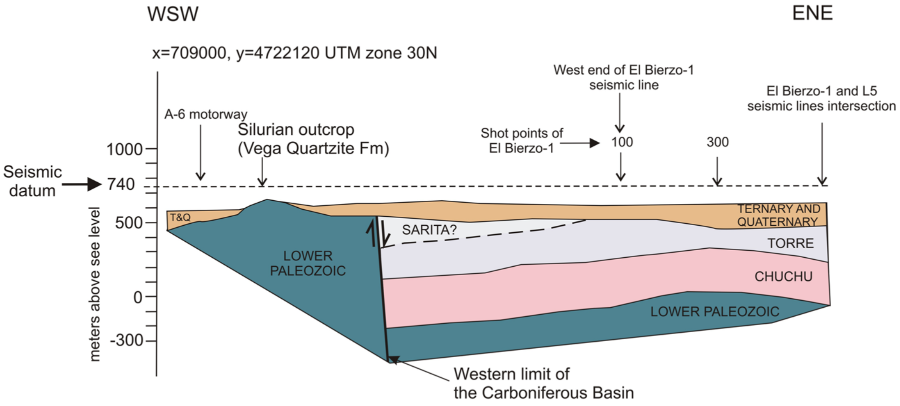

Figure 6 Geological profile depicting the faulted western limit of the Carboniferous basin deduced from geological and seismic data (see location in Fig. 1b, green line). This profile extends further west in the geological map (Fig. 1b). El Bierzo-1 seismic line in the east partially covers the profile.

Unfortunately, due to logistic problems, the Bierzo-1 seismic reflection profile does not cross the western limit of Torre-Bembibre sub-basin. The seismic data obtained, nevertheless, provide us some clues to interpret that boundary. The interpretation of the western part of the profile and some isolated outcrops of Silurian rocks to the west, outside the study area, made possible to draw an E–W geological profile (Fig. 6; see location in Fig. 1b). As seen in Bierzo-1 (Fig. 3), there is a smooth anticline in the Carboniferous base unconformity. The Carboniferous strata show westward dipping towards the end of the profile. Supporting geological data allow the prolongation of the Chuchu, Torre and Sarita strata, which can be interpreted as to be maintaining their dip and thickness in an approximate sense (Fig. 6).

The western Silurian outcrops help support the hypothesis of a faulted westernmost limit of the Carboniferous basin under the Tertiary cover. As drawn in Fig. 6, the most plausible interpretation shows an SSW–NNE normal fault with its footwall block extending to the west. Considering nearly 1000 m of vertical displacement, the Carboniferous sediments seem to be completely eroded under the Tertiary at the footwall block, which is consistent with the presence of the Silurian under the Tertiary base (and the absence of Carboniferous) in the afore-mentioned outcrops. Despite the interpretation depicted in Fig. 6, any possible fault fossilization at an indeterminate level of the Tertiary cover, as well as the presence of Sarita, remains unclear.

TORRE-BEMBIBRE SUB-BASIN AS A POTENTIAL CO_2 RESERVOIR

In order to evaluate the potential of the Torre-Bembibre sub-basin as a CO_2 reservoir, the 3D model had to be complemented with basic geometric and petrophysical data. The geological model indicated that Chuchu and Torre strata were the most favourable ones in view of their depth and sand–shale content.

The only logged boreholes are TB-9 (neutron, gamma ray (GR), and bed resolution density (BRD) logs) and TB-10 (neutron, GR, BRD, and spontaneous potential (SP) logs). Whereas TB-9 reaches neither the Torre layer nor the Chuchu, TB-10 reaches the complete Torre layer and 40 m of the Chuchu. Neutron and GR logs provide data on porosity, sand–shale content and so on for the Torre and Chuchu strata.

The syncline/anticline shape of the Torre-Bembibre sub-basin is defined in the 3D modelling (Fig. 5). The E–W geological profile (Fig. 6) suggests that a significant volume is probably found under the Tertiary cover, indicating the possibilities to store CO_2. The Tertiary strata, which unconformably cover the possible reservoir, should act as a seal. However,

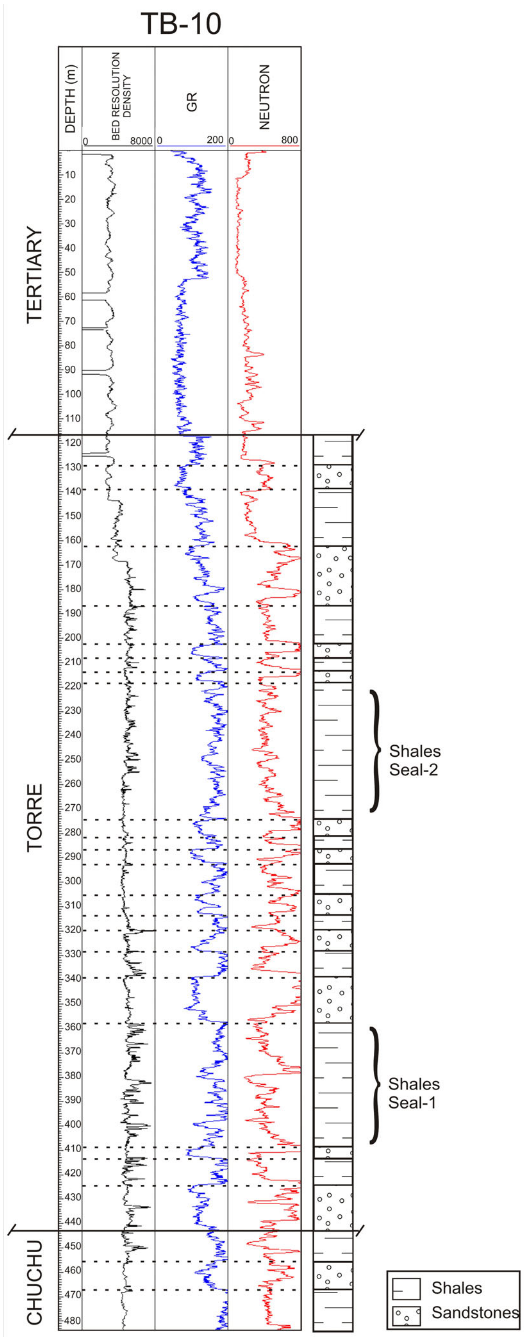

Figure 7 Bed resolution density (BRD), gamma ray (GR) and neutron logs of the TB-10 borehole. The interpretation indicates the presence of two potential sealing shale levels indicated as seal-1 and seal-2 within the Torre package.

Table 1 Reservoir parameters. Effective thickness: proportion of sand enables to contain CO_2. CO_2 density deduced at 800 meters mean depth (Bachu, 2003). Capacity = Total volume *Effective thickness $^*CO_2$ density *Porosity *Efficiency factor.

Parameters		Reservoir	Seal
	Top deepness (m)	800	750
	Thickness (m)	350	50
	Lithology	Sand–shale	Shale
	% of shales	50	85 (interbedded coal)
	Effective thickness (%)	50	85 (interbedded coal)
	Porosity (%)	5–10	
Geometry	Morphology	Gentle anticline	
	Area (km^2)	18.2	
Reservoir capacity	CO_2 density (kg/m^3)	100	
	Efficiency factor	0.3	
	Effective porosity	0.07	
	Capacity (Mt)	7	

the good quality of the seal must be evaluated because, although less permeable layers (Toral Formation) are found at the base, they present a great number of sand and gravel beds that could question the sealing capacity. On the other hand, the outcropping of all the intra-Carboniferous strata (Anchas, Estrechas, Chuchu-Navaleo, Torre, Sarita, Nueva, Constancia and Superior) would be incompatible with a closure of the reservoir in the east–southeast part of the Torre-Bembibre sub-basin.

Interpretation of the TB-10 borehole logs (Fig. 7) provides the sand–shale ratios throughout the Torre layer, where two deduced, thick shale levels (seals-1 and 2 in Fig. 7) could become an excellent seal for a reservoir. For the deepest shale level (seal-1 in Fig. 7), the potential reservoir corresponds mainly to the underlying Chuchu. The Chuchu level is crossed by three boreholes (TB-4, TB-5 and TB-6), whose lithological interpretation points to a sand–shale ratio close to the 50% for the whole formation. The calculated porosity of the seal-1 is 5%–10%. The reservoir top lies 800 m below the anticline north of the South Bembibre thrust fault. In light of all these figures, the total reservoir capacity is summarized in Table 1.

Figure 8 shows a view from the south of the potential CO_2 reservoir. Its base corresponds to the base of Carboniferous surface and its top to seal-1 in the Torre layer (Fig. 7). The west reservoir limit corresponds to the deduced normal fault discussed above, and the south boundary to the South Bembibre thrust fault. The northern boundary fits with the Brañuelas thrust fault. The only possible closure of the reservoir eastwards is located at the bottom of Carboniferous Chuchu base of the Torre anticline, which was deduced through modelling (see Figs 5 and 6). Taking these four limits into account, along with the considerations discussed earlier, the total volume is estimated at 6.4 km^3, and the total capacity for CO_2

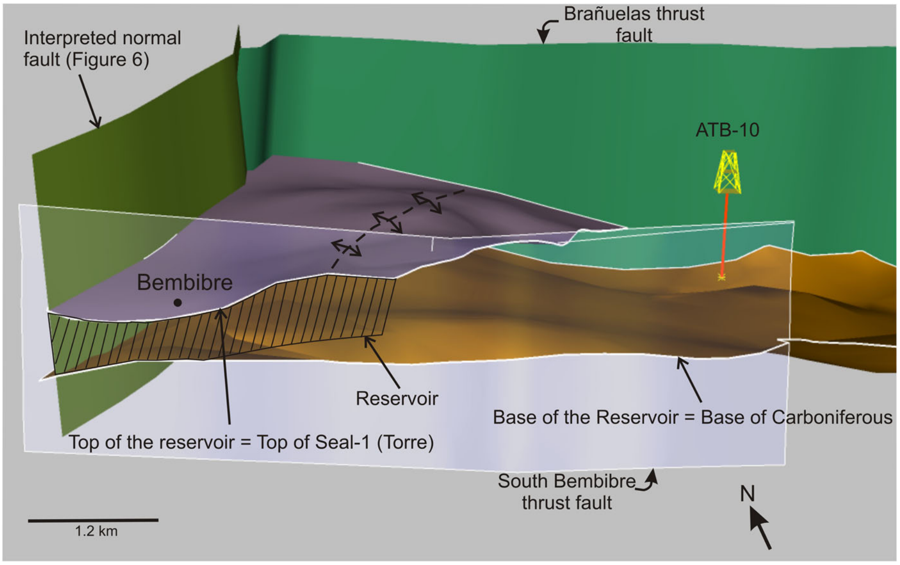

Figure 8 View from south of the potential CO_2 reservoir. The striped area in black represents the volume of the reservoir. The limits of the reservoir are the base of Carboniferous (anticline in the centre), the intra-Torre level (seal-1) on top, a normal fault in the west, the Brañuelas fault to the north and the Bembibre thrust fault in the south.

storage can potentially reach 7 Mt. The reservoir is envisaged within the major massive sandstone bodies associated with the Chuchu formation – the syncline–anticline geometry north of the town of Bembibre (Fig. 8).

Although the geometry and potential volume are well delimited, a drawback of this potential CO_2 storage reservoir is its depth. Shallow reservoirs imply lesser CO_2 density; previous studies report that CO_2 reaches its supercritical state at depths of ~800 m below the surface (Holloway and Savage 1993; van der Meer 1993; Bachu 2003).

Further studies are needed to ensure the suitability of the Chuchu layer as a reservoir. Along these research lines, more investigations should be carried on, for example, gravity or electromagnetic surveys, to ascertain the precise geometry of the Carboniferous Lower Paleozoic unconformity and the intra-Carboniferous levels. If these results are positive, then further seismic work and drilling should be performed.

CONCLUSIONS

A study to assess the potential of the Torre-Bembibre sub-basin in NW Spain as a CO_2 storage reservoir was undertaken to derive a full 3D geological basin model. The 3D dip-domain method contributed to the definition of a consistent geometry for the modelled surfaces, fully enclosed within a single structural frame. The results from surface reconstruction were integrated with geophysical subsurface information, allowing the model to reach the deepest part of the basin under the Tertiary cover.

The Torre-Bembibre sub-basin can be described as having a gentle syncline geometry, with its axis pinching westwards. The depth of the Carboniferous strata increases to the northeast, reaching depths of over 1500 m below the topographic surface. To the west, the geometry shifts into an anticline that maintains the N–S trend. The anticlinal shape allows the Carboniferous depth values to be shallow – to only 900–1000 m north of the South Bembibre thrust fault. The western limit of the Torre-Bembibre sub-basin corresponds to a normal fault, as inferred from modelling.

The syncline/anticline geometry of the Torre-Bembibre sub-basin suggests that a potential CO_2 reservoir may be present under the Tertiary cover. Available borehole logs inform that intra-Carboniferous shale levels could provide an excellent seal. The reservoir would mainly be located in the interbedded sandstones of the Chuchu strata, with a porosity of 5%–10%. The total estimated volume is 6.4 km^3, and the total capacity of the storable CO_2 storage reaches 7 Mt. The top of the reservoir would lie at around 800 m and its base at about 1050 m below the surface. The capacity of the reservoir is promising enough to merit further studies, for instance implementing the proposed 3D geological model in terms of petrophysics and geometry, especially nearby the town of Bembibre.

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