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Active tectonic field for CO_2 Storage management: Hontomín onshore study-case (SPAIN)

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Abstract

One of the concerns of underground CO_2 ~~onshore~~ storage is the triggering of Induced Seismicity and fault reactivation. Hence, a comprehensive analysis of the tectonic parameters involved in the storage rock formation is mandatory for safety management operations. Unquestionably, active faults and seal faults depicting the storage bulk are relevant parameters to be considered. However, there is a lack of analysis of the active tectonic strain field affecting these faults during the CO_2 storage monitoring. The advantage of reconstructing the tectonic field is the possibility to determine the strain trajectories and describing the fault patterns affecting the reservoir rock. In this work, we adapt a methodology of systematic geostructural analysis to the underground CO_2 storage, based on the calculation of the strain field and defined by the strain field from kinematics indicators on the fault planes (e_y and e_x for the maximum and minimum horizontal shortening respectively),. This methodology is based on a statistical analysis of individual strain tensor solutions obtained from fresh outcrops. Consequently, we have collected 447 fault data in 32 field stations located within a 20 km radius. The understanding of the fault sets role for underground fluid circulation can also be established, helping for further analysis of CO_2 leakage and seepage. We have applied this methodology to Hontomín onshore CO_2 storage facilities (Central Spain). The *geology of the area and the number of high-quality outcrops made this site ~~as~~ a good candidate for studying the strain field from kinematic~~s~~ fault analysis. The results indicate a strike-slip tectonic regime with the maximum horizontal shortening with N160°E and N50°E trend for the local regime, which activates NE-SW strike-slip faults and NE-SW compressional faults. A regional tectonic field was also recognized with a N-S trend, which activates E-W compressional faults. Monitoring of E-W faults within the reservoir is suggested in addition to the possibility of obtaining focal mechanism solutions for microearthquakes (M < 3).*

Keywords: onshore CO_2 storage, tectonic field, paleostrain analysis, active fault, Hontomín onshore pilot-plant.

1. INTRODUCTION

Industrial made-man activities generate CO_2 that could change the chemical balance of the atmosphere and their relationship with the geosphere. Carbon capture and sequestration (CCS) appears as a good choice to reduce the CO_2 gas emission to the atmosphere (Christensen, 2004), allowing the industry increasing activity with a low pollution impact. There is a lot of literature about what must have a site to be a potential underground storage suitable to CCS (e.g. Chu, 2009; Orr, 2009; Goldberg et al., 2010 among others). The reservoir sealing, the caprock, permeability and porosity, plus injection pressure and volume injected, are the main considerations to choose one geological subsurface formation as the CO_2 host-rock. In this frame, the tectonic active field is considered in two principal ways: (1) to prevent the fault activation and earthquake~~s~~ triggering, with the consequence of leakage and seepage, and (2) the long-term reservoir behavior, understanding as long-term from centennial to millennial timespan. Therefore, what is the long-term behavior of CCS? What do we need to monitor for a safe CCS management? Winthaegen et al. (2005) suggest three subjects for monitoring: (a) the atmosphere air quality near the injection facilities, due to the CO_2 toxicity (values greater than 4%, see Rice, 2003 and Permentier et al., 2017), (b) the overburden monitoring faults and wells and (c) the sealing of the reservoir. The study of natural analogues for CCS is a good strategy to estimate the long-term behavior of the reservoir, considering parameters as the injected CO_2 pressure and volume, plus the brine mixing with CO_2 (Pearce, 2006). Hence, the prediction of site performance over long timescales also requires an understanding of CO_2 behavior within the reservoir, the mechanisms of migration out of the reservoir, and the potential impacts of a leak on the near surface environment. The assessments of such risks will rely on a combination of predictive models of CO_2 behavior, including the fluid migration and the long-term CO_2-porewater-mineralogical interactions (Pearce, 2006). Once again, the tectonic active field interacts directly on this assessment. Moreover, the fault reactivation due to the pore pressure increasing during the injection and storage has also to be considered (Röhmann et al., 2013). Despite the uplift measure by Röhmann et al. (2013) ~~are~~ submillimeter (c.a. 0.021 mm) at the end of the injection processes, given the ongoing occurrence of microearthquakes, long-term monitoring is required. The geomechanical and geological models predict the reservoir behavior and the caprock sealing properties. The role of the faults inside these models is crucial for the tectonic long-term behavior and the reactivation of faults that could trigger earthquakes.

Concerning the Induced Seismicity, Wilson et al. (2017) published the Hi-Quake database, with a classification of all man-made earthquakes according to the literature, in an online repository (https://inducedearthquakes.org/, last access on May, 2019). This database includes 834 projects with proved Induced Seismicity, where two different cases with earthquakes as larger as M 1.7, detected in swarms about 9,500 microearthquakes, are related to CCS operations. Additionally, Foulger et al. (2018) pointed out that CCS can trigger earthquakes with magnitudes lesser than M 2, namely the cases described in their work are as greater as M 1.8, with the epicenter location 2 km around the facilities. McNamara (2016) described a comprehensive method and protocol for monitoring CCS reservoir for the assessment and management of Induced Seismicity. The knowledge of active fault patterns and the stress/strain field could help on designing monitoring network and identifying those faults capable for triggering micro-earthquakes ($M < 2$) and/or breaking the sealing for leakage (~~patterns~~ of open faults for low-permeability CO_2 migration).

In this work, we propose that the description, the analysis and establishment of the tectonic strain field have to be mandatory for long-term CCS monitoring and management, implementing the fault behavior in the geomechanical models. This analysis does not increase the cost ~~for~~ long-term monitoring, given that they are low-cost and the results are acquired in a few months. Therefore, we propose a methodology based on the reconstruction of the strain field from the classical studies in geodynamics (Angelier, 1979 and 1984; Reches, 1983; Reches, 1987). As a novelty, we introduce the strain fields (SF) between 20 away from the subsurface reservoir deep geometry. The knowledge of the strain field at local scale allows to classify the type of faulting and their role for leakage processes, whilst the regional scale explores the tectonic active faults which could affect the reservoir. The methodology is rather simple, taking measures of slickensides and striations on fault planes to establish the orientation of the maximum horizontal shortening (e_y), and the minimum horizontal shortening (e_x) for the strain tensor. The principal advantage of the SF analysis is the direct~~ly~~ classification of all the faults involved in~~to~~ the geomechanical model and the prediction of the failure parameters.

The tectonic characterization of the CCS of Hontomín was implemented in the geological model described by Le Gallo and de Dios (2018). Beyond the use of Induced Seismicity and potentially active faults, the scope of this method is to propose an initial protocol to manage underground storage operations.

2. HONTOMÍN ONSHORE STUDY CASE

2.1 Geological description of the reservoir

The CO_2 storage site of Hontomín is enclosed in the southern section of the Mesozoic Basque–Cantabrian Basin, known as Burgalesa Platform (Serrano and Martinez del Olmo, 1990, Tavani, 2012), within the sedimentary Bureba Basin (**Fig. 1**). This geological domain is located in the northern junction of the Cenozoic Duero and Ebro basins, forming an ESE-dipping monocline bounded by the Cantabrian Mountains Thrust to the north, the Ubierna Fault System (UFS) to the south and the Asturian Massif to the west (**Fig. 1**).

The Meso-Cenozoic tectonic evolution of the Burgalesa Platform starts with a first rift period during Permian and Triassic times (Calvet et al., 2004; Dallmeyer and Martínez-García, 1990), followed by a relative tectonic quiescence during Early and Middle Jurassic times (e.g. Aurell et al., 2002). The main rifting phase took place during the Late Jurassic and Early Cretaceous times, due to the opening of the North Atlantic and the Bay of Biscay-Pyrenean rift system (García-Mondéjar et al., 1986; García-Mondéjar et al., 1996; Le Pichon and Sibuet, 1971; Lepvrier and Martínez-García, 1990; Roca et al., 2011; Tugend et al., 2014). The convergence between Iberia and Eurasia from Late Cretaceous to Miocene times triggered the inversion of previous

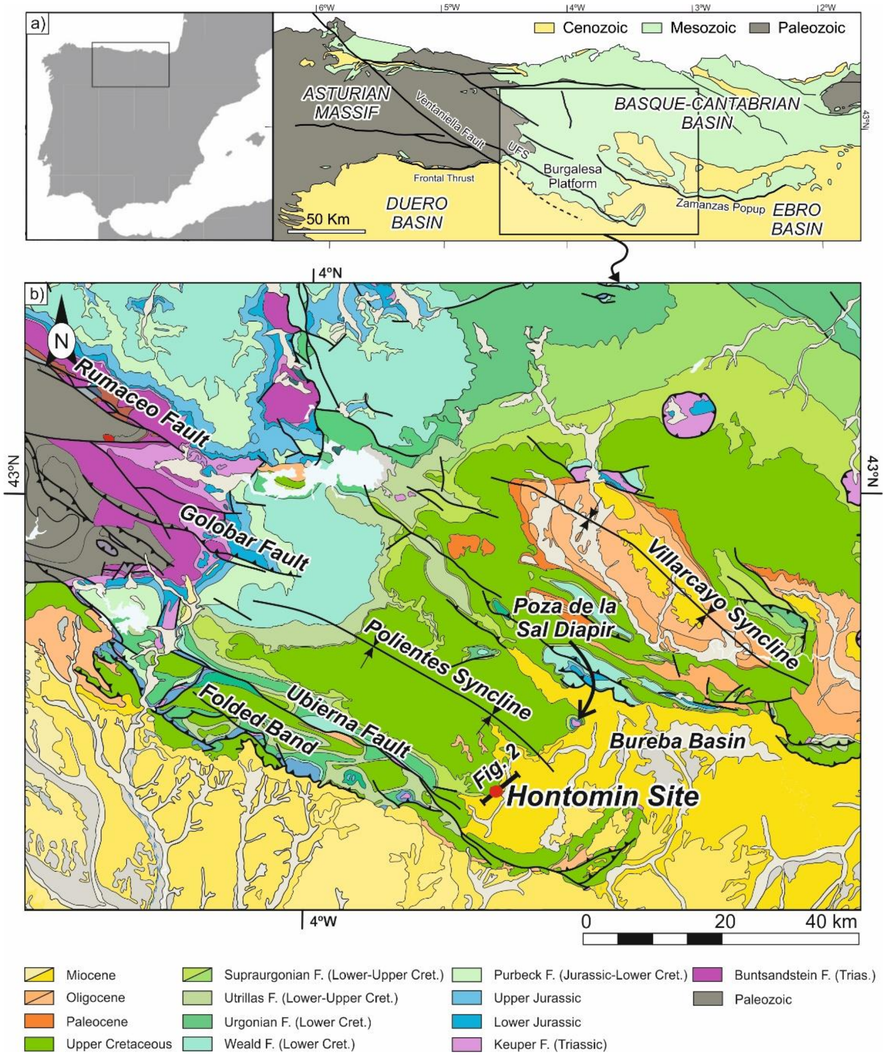

Figure 1. a) Location map of the study area in the Iberian Peninsula, along with the geological map of the Asturian and Basque-Cantabrian areas, labelling major units and faults (modified after Quintà and Tavani 2012); b) Geographical location of Hontomín pilot-plant (red dot) within the Basque-Cantabrian Basin. This basin is tectonically controlled by the Ubierna Fault System (UFS; NW-SE oriented) and the parallel Polientes syncline, the Duero and Ebro Tertiary basins and Poza de la Sal evaporitic diapir. Cret: Cretaceous; F: Facies.

Mesozoic extensional faults and the development of a E-W orogenic belt (Cantabrian domain to the west and Pyrenean domain to the east) formed along the northern Iberian plate margin (Gómez et al., 2002; Muñoz, 1992; Vergés et al., 2002).

The facilit~~ies~~ ~~are~~ located within the Basque-Cantabrian Basin (**Fig. 1b**). This reservoir is a deep saline aquifer developed in fractured Jurassic carbonates, with a low porous permeability matrix, located at almost 1,500 m depth (Alcalde et al., 2013). The Hontomín geological structure was described by Alcalde et al. (2013) and Le Gallo and de Dios (2018), and defined as a fold-related dome (Tavani et al., 2013). The reservoir structure is associated to the Cenozoic extensional tectonic stages, according to these authors. The present-day geological structure is related with the reactivation by a tectonic compressional phase during the Cenozoic Pyrenees compression (Alcalde et al., 2013).

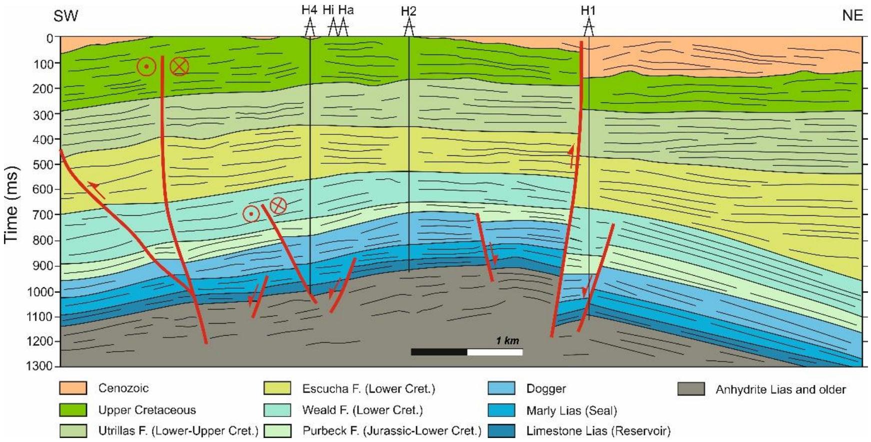

Figure 2: Interpretation of a 2D seismic reflection profile crossing the oil exploration wells (H1, H2 and H4), along with the monitoring well (Ha) and injection well (Hi) through Hontomin Pilot Plant (HPP). Modified from Alcalde et al. (2014). See Figure 1 for location, black line at the red circle.

The Hontomín structure is bordered by the UFS to the south and west, by the Poza de la Sal diapir and the Zamanzas Popup structure (Carola, 2014) to the north and by the Ebro Basin to the east (**Fig. 1**). The structure has been classified as forced fold related dome structure (Tavani et al., 2013; **Fig. 2**), which was formed by an extensional fault system with migration of evaporites towards the hanging wall during the Mesozoic (Soto et al., 2011). During the tectonic compressional phase, associated with Cenozoic tectonics affecting the Pyrenees, the right-lateral transpressive inversion of the basement faults was activated, plus the reactivation of transverse extensional faults (**Fig. 2**; Tavani et al., 2013; Alcalde et al., 2014).

At the HPP, the target reservoir and seal formations consist of Lower Jurassic marine carbonates, arranged in an asymmetric dome-like structure (**Fig. 2**) with an overall extent of 15 km^2 and located at 1,485 m of depth (Alcalde et al., 2013, 2014; Ogaya et al., 2013). The target CO_2 injection point is a saline aquifer formed by a dolostone unit, known as “Carniolas”, and an oolitic limestone of the Sopeña Formation, both corresponding to Lias in time (Early Jurassic). The estimated porosity of the Carniolas reaches over 12% (Ogaya et al., 2013; Le Gallo and de Dios, 2018) and it is slightly lower at the Carbonate Lias level (8.5% in average). The reservoir levels contain saline water with more than 20 g/l of NaCl and very low oil content. The high porosity of the lower part of the reservoir (i.e., the Carniolas level) is the result of secondary dolomitization and different fracturing events (Alcalde et al., 2014). The minimum thickness of the reservoir units is 100 m. The potential upper seal unit comprises Lias marlstones and black shales from a hemipelagic ramp (**Fig. 2**); Pliensbachian and Toarcian) of the “Puerto del Pozazal” and Sopeña Formations.

2.2 Regional tectonic field

The tectonic context of HPP has been described from two different approaches: (1) the tectonic style of the fractures bordering the Hontomín reservoir (De Vicente et al., 2011; Tavani et al., 2011) and (2) the tectonic regional field described from earthquakes with mechanism solutions and GPS data (Herraiz et al., 2000; Stich et al., 2006; De Vicente et al., 2008).

(1) The tectonic style of the Bureba Basin was described by De Vicente et al. (2011), which classified the Basque-Cantabrian Cenozoic Basin (**Fig. 1a**) as transpressional with contractional horsetail splay basin. The NW-SE oriented Ventaniella fault (**Fig. 1a**), includes the UFS in the southeastward area, being active between the Permian and Triassic period, and strike-slip during the Cenozoic contraction. In this tectonic configuration, the Ubierna Fault is a right-lateral strike-slip fault. These authors pointed out the sharp contacts between the thrusts and the strike-slip faults in this basin. Furthermore, Tavani et al. (2011) also described complex Cenozoic tectonic context where right-lateral tectonic style reactivated WNW-ESE trending faults. Both the Ventaniella and the Ubierna faults acted as transpressive structures forming 120 km long and 15 km wide of the UFS, and featured by 0.44 mm/yr of averaged tectonic strike-slip deformation between the Oligocene and the present day. The aforementioned authors described different surface segments of the UFS of right-lateral strike-slip ranging between 12 and 14 km length. The structural data collected by Tavani et al. (2011) pointed out the 60% of data correspond to right lateral strike-slip with WNW-ESE trend, together with conjugate reverse faulting with NE-SW, NW-SE and E-W trend, and left-lateral strike-slip faults N-S oriented. They concluded that this scheme could be related to a transpressional right-lateral tectonic system with a maximum horizontal compression, S_{Hmax}, striking N120ºE. Concerning the geological evidence of

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recent sediments affected by tectonic movements of the UFS, Tavani et al. (2011) suggest Middle Miocene in time for this tectonic activity. However, geomorphic markets (river and valley geomorphology) could indicate activity at present-times. All of these data correspond to regional or small-scale data collected to explain the Basque-Cantabrian Cenozoic transpressive basin. The advantage of the methodology proposed here to establish the tectonic local regime affecting the reservoir, is the searching for local-scale tectonics (20 km sized), and the estimation of the depth for the non-deformation surface for strata folding in transpressional tectonics (Lisle et al., 2009).

(2) Regarding the stress field from earthquake focal mechanism solutions, Herraiz et al. (2000) pointed out the regional trajectories of S_{Hmax} with NNE-SSW trend, and with a NE-SW S_{Hmax} trend from slip-fault inversion data. Stich et al. (2006) obtained the stress field from seismic moment tensor inversion and GPS data. These authors pointed out a NW-SE Africa-Eurasia tectonic convergence at tectonic rate of 5 mm/yr approximately. However, no focal mechanism solutions are found within the Hontomín area (20 km) and only long-range spatial correlation could be made with high uncertainty (in time, space and magnitude). The same lack of information appears in the work of De Vicente et al. (2008), with no focal mechanism solutions in the 50 km surrounding the HPP. In this work, these authors classified the study area as uniaxial extension to strike-slip with NW-SE S_{Hmax} trend.

Regional data about the tectonic field within the HPP (Bureba basin), inferred from different works (Herraiz et al., 2000; Stich et al., 2006; De Vicente et al., 2008, 2011; Tavani et al., 2011; Tavani, 2012), show differences for the S_{Hmax} trend. These works explain the tectonic framework for regional scale, nevertheless local tectonics could determine the low permeability and the potential Induced Seismicity within the Hontomín reservoir. In the next section, we have applied the methodology described at the section 3 of this manuscript, in order to compare the regional results from these works and to establish the tectonic evolution of the Burgalesa Platform.

2.3 Strategy of the ENOS European Project

Hontomín pilot-plant (HPP) for CO_2 onshore storage is the only one in Europe recognized as a key-test-facility, and it is managed ~~and conducted~~ by CIUDEN (*Fundación Ciudad de la Energía*). This HPP is located within the province of Burgos (**Fig. 1b**), in the northern central part of Spain.

The methodology proposed in this work and its application for long-term onshore CCS managing in the frame of geological risk, is based on the strain tensor calculation, as part of the objectives proposed in the European project ENOS. The ENOS project is an initiative of CO2GeoNet, the European Network of Excellence on the geological storage of CO_2 for supporting onshore storage and fronting the associated ~~troubles~~ as CCS perception, the safe storage operation, potential leaking management and health, and environmental safety (Gastine et al., 2017). ENOS combines a multidisciplinary European project, which focuses in onshore storage, with the demonstration of best practices through pilot-scale projects in the case of Hontomín facilities. Moreover, this project claims for creating a favorable environment for CCS onshore through public engagement, knowledge sharing, and training (Gastine et al., 2017). In this context, the work-package WP1 is devoted to “ensuring safe storage operations”. The IGME team is committed to develop and to carry out a ~~technology~~ to determine the active strain-field affecting the sub-surface reservoir and fault patterns and to assign the fault type for the estimation of potential fault-patterns as low-permeability paths as well.

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3. METHODS AND RATIONALE

The lithosphere remains in a permanent state of deformation, related to plate tectonics motion. Strain and stress fields are the consequence of this deformation on the upper lithosphere, arranging different fault patterns that determine sedimentary basins and geological formations. Kinematics of these faults describes the stress/strain fields, for example measuring grooves and slickensides on fault planes (see Angelier, 1979, Reches, 1983 among others). The relevance of the tectonic field is that stress and strain determine the earthquake occurrence by the fault activity. In this work, we have performed a brittle analysis of the fault kinematics, by measuring slickenfiber on fault planes in several outcrops in the surroundings of the ~~onshore~~ reservoir. These faults were active during the Mesozoic, and from Late Miocene to Quaternary. To carry out the methodology proposed in this work, the study area was divided in a circle with four equal areas, and we searched outcrops of fresh rock to perform the fault kinematic analysis. This allows establishing a realistic tectonic very-near field to be considered during the storage seismic monitoring and long-term management.

~~2.1~~ *Paleostrain Analysis*

We have applied the strain inversion technique to reconstruct the tectonic field (paleostrain evolution), affecting the Hontomín site between the Triassic, Jurassic, Cretaceous and Neogene ages (late Miocene to present times). For a further methodology explanation see Etchecopar et al. (1981), Reches (1983) and Angelier (1990). The main assumption for the inversion technique of fault population is the self-similarity to the scale invariance for the stress/strain tensors. This means that we can calculate the whole stress/strain fields by using the slip data on fault planes and for homogeneous tectonic frameworks. The strain tensor is an ellipsoid defined by the orientation of the three principal axes and the shape of the ellipsoid (k). This method assumes that the slip-vectors, obtained from the pitch of the striation on different fault planes, define a common strain tensor or a set in a homogeneous tectonic arrangement. We assume that the strain field is homogeneous in space and time, the number of faults activated is greater than five and the slip vector is parallel to the maximum shear stress (τ).

The inversion technique is based on the Bott equations (Bott, 1959). These equations show the relationship between the orientation and the shape of the stress ellipsoid:

$$\mathrm{Tan}\,(\theta) = [n / (l * m)] * [m^2 - (1- n^2) * R'] \qquad [\mathrm{eq.1}]$$

$$R' = (\sigma_z - \sigma_x) / (\sigma_y - \sigma_x) \qquad [\mathrm{eq.2}]$$

Where l, m and n are the direction cosines of the normal to the fault plane, θ is the pitch of the striation and R' is the shape of the stress ellipsoid obtained in an orthonormal coordinate system, x, y, z. In this system, σ_y is the maximum horizontal stress, σ_x is the minimum horizontal stress axis and σ_z is the vertical stress axis.

3.2 The Right-Dihedral Model for Paleostrain Analysis

The Right-Dihedral (RD) is a semi-quantitative method based on the overlapping of compressional and extensional zones by using a stereographic plot. The final plot is an interferogram figure which usually defined the strain-regime. This method is strongly robust for conjugate fault sets and with different dip values for a same tensor. The RD was originally defined by Pegoraro (1972) and Angelier and Mechler (1977), as a geometric method, adjusting the measured fault-slip data (slickensides) in agreement with theoretical models for extension and compressive fault-slip. Therefore, we can constraint the regions of maximum compression and extension related to the strain regime.

3.3 The Slip Model for the Paleostrain Analysis

The Slip Model (SM) is based on the Navier-Coulomb fracturing criteria (Reches, 1983), taking the Anderson model solution for this study (Anderson, 1951; Simpson, 1997). The Anderson model represents the geometry of the fault plane as monoclinic, relating the quantitative parameters of the shape parameter (K') with the internal frictional angle for rock mechanics (ϕ) (De Vicente 1988, Capote et al., 1991). Moreover, this model is valid for neoformed faults, and some considerations have to be accounted for previous faults and weakness planes present in the rock. These considerations are related to the dip of normal and compressional faults, such as for compressional faulting values lower than $b < 45^o$, reactivated as extensional faults. This model shows the relationships between the K', ϕ and the direction cosines for the striation on the fault plane (De Vicente, 1988; Capote et al., 1991):

$$K' = e_y / e_z \qquad \text{[eq.3]}$$

Where e_z is the vertical strain axis, e_y is the maximum horizontal shortening and e_x is the minimum horizontal shortening. This model assumes that there is no change of volume during the deformation and $e_y = e_x + e_z$.

For isotropic solids, principal strain axes coincide with the principal stress axes. This means that in this work, the orientation of the principal stress axis, S_{Hmax} is parallel to the orientation of the principal strain axes, e_y, and hence, the minimum stress axis, S_{hmin}, is parallel to the minimum strain axis, e_x. This assumption allows us to estimate the stress trajectories (S_{Hmax} and S_{hmin}) from the De_y SM results.

Resolving the equations of Anderson (Anderson, 1951) for different values, we can classify the tectonic regime that activates one fault from the measurement of the fault dip, sense of dip and pitch of the slickenside, assuming that one of the principal axes (e_x, e_y or e_z) are vertical (Angelier, 1984). We can classify of the tectonic regime and represent the strain tensor by using the e_y and e_x orientation.

3.4 The K' strain diagram

Another analysis can be achieved by using the K'-strain diagram developed by Kaverina et al. (1996) and codified in python-code by Álvarez-Gómez (2014). These authors have developed a triangular representation based on the fault-slip, where tectonic patterns can be discriminated between strike-slip and dip-slip types. This diagram is divided in 7 different zones according to the type of fault: (1) pure normal, (2) pure reverse and (3) pure strike-slip, combined with the possibility of oblique faults: (4) reverse strike-slip and (5) strike-slip with reverse component, and lateral faults: (6) normal strike-slip and (7) strike-slip faults with normal component (**Fig. 3**). Strike-slip faults are defined by small values for pitch ($p < 25º$) and dips close to vertical planes ($\beta > 75º$). High pitch values ($p > 60º$) are related to normal or/reverse fault-slip vectors. Extensional faults show e_y in vertical whereas compressional faults show e_y in horizontal plane.

This method was originally performed for earthquake focal mechanism solutions by using the focal parameters, the nodal planes (dip and strike) and rake. The triangular graph is based on the equal-areal representation of the T, N or B and P axes in spherical coordinates (T tensile, N or B neutral and P pressure axes), and the orthogonal regression between Ms and mb for the Harvard earthquake CMT global catalogue in

1996. Álvarez-Gómez (2014) presented a code python-based for computing the Kaverina diagrams, and we have modified the input parameters by including the K' intervals for the strain field from the SM. The relationship between the original diagram of Kaverina (**Fig. 3a**) and the K'-dip diagram (**Fig. 3b**) that we have used in this work is shown in the figure 3. The advantage of this diagram is the fast assignation of the type of fault and the tectonic regime that determine this fault pattern, and the strain axes relationship.

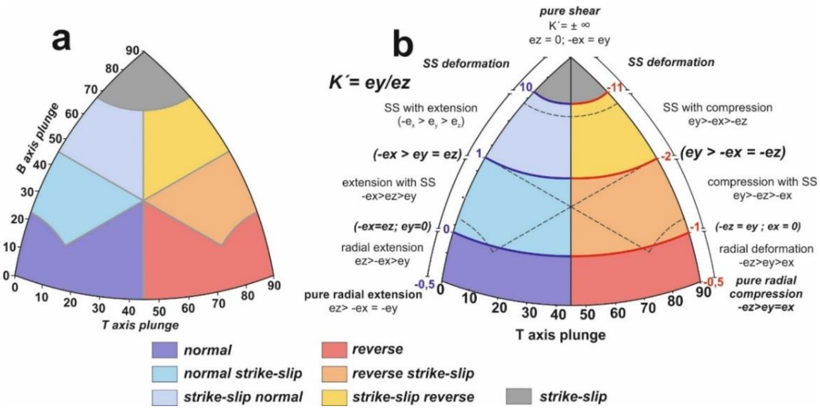


Figure 3. a) Kaverina original diagram to represent the tectonic regime from an earthquake focal mechanism population (see Kaverina et al., 1996 and Álvarez-Gómez, 2014). b) K'-strain diagram used in this work. Dotted lines represent the original Kaverina limits. Colored zones represent the type of fault. The tectonic regime is also indicated by the relationship between the strain axes and the colored legend. SS Strike slip. The B axis is the orthogonal to the P and T axes.

Table 1 summarizes the different tectonic regimes of the figure 3b showing the relationship with the strain main axes e_y, e_x and e_z. This diagram exhibits a great advantage to classify the type of fault according to the strain tensor. Therefore, we can assume the type of fault from the fault orientation affecting geological deposits for each strain tensor obtained.

K’	*T-axis*	*strain axis rel.*	*fault type*	*tectonic field*
< - 0.5	0º	$e_z>-e_x=-e_y$	normal	pure radial extension
-0.5<K’<0	0º-45º	$e_z>-e_x>-e_y$	normal	radial extension
K’=0	0º-45º	$e_z=-e_x;\ e_y=0$	normal	plain strain
0<K’<1	0º-45º	$-e_x>e_z>e_y$	normal with SS	extension with shear
k=1	0º-45º	$-e_x>e_y=e_z$	normal with SS	extension with shear
1<K’<10	0º-45º	$-e_x>e_y>e_z$	strike-slip with N	shear with extensional
10<K’<∞	0º-45º	------------	strike-slip	shear deformation
K’=∞	45º	$e_z=0;-e_x=e_y$	strike-slip	pure shear deformation
∞<K’<-11	45º-90º	------------	strike-slip	shear deformation
-11<K’<-2	45º-90º	$e_y>-e_x>-e_z$	strike-slip with R	shear with compression
K’=-2	45º-90º	$e_y>-e_x=-e_z$	reverse with SS	compression with shear
-2<K’<-1	45º-90º	$e_y>-e_z>-e_x$	reverse with SS	compression with shear
K’=-1	45º-90º	$-e_z=e_y;\ e_x=0$	reverse	plain strain
-1<K’<-0.5	45º-90º	$-e_z>e_y>e_x$	reverse	radial compression
K’=-0.5	45º-90º	$-e_z>e_y=e_x$	reverse	pure radial compression

SS = strike-slip
N= normal
R= reverse

e_x = value of the minimum horizontal shortening
e_y = value of the maximum horizontal shortening
e_z = value of the vertical axis

Table 1. Different tectonic regimes, K’ values, dip values and fault type for the Kaverina modified diagram used in this work. According to the strain axes relationship, faults can be classified and the tectonic regime can be established.

3.5 The Circular-Quadrant-Search (CQS) strategy for the paleostrain analysis

In this work, we propose a low-cost strategy based on a well-known methodology for determining the stress/strain tensor affecting a CCS reservoir, which will allow for monitoring long-term geological and seismic behavior. The objective is to obtain enough structural data and spatially homogeneous of faults (**Figs. 4, ~~5~~**), for reconstructing the stress/strain tensor by using the methodologies described above. The key-point is the determination of the orientation of the e_y, e_x and K’ to plot in a map and therefore, to establish the tectonic regime. We have chosen quadrants of the circles with the aim to obtain a high-quality spatial distribution of point for the interpretation of the local and very near strain field. ~~Hence, data are homogeneously distributed, instead of being only concentrated in one quadrant of the circle~~.

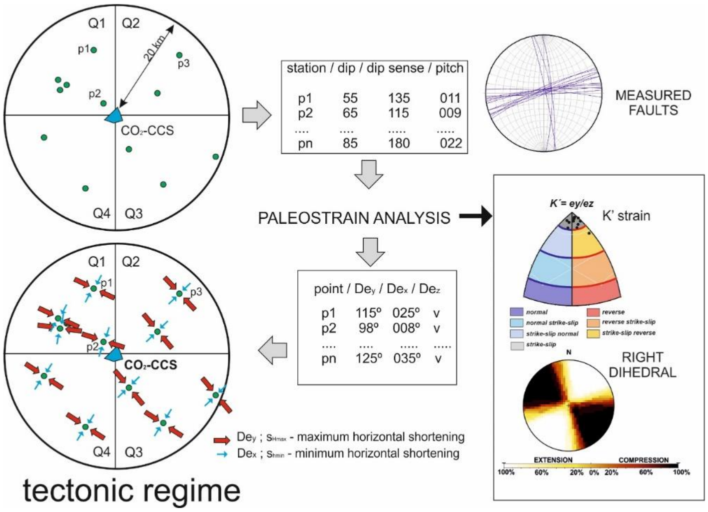


Figure 4. Methodology proposed to obtain the strain field affecting the CCS reservoir. The distances for outcrops and quadrants proposed is 20 km. The technique of Right Dihedral and the K' strain diagram is described in the main text. The e_y *and* e_x *represented are a model for explaining the methodology.* De_y *and* De_x *are the direction of the maximum and minimum strain, respectively. Blue box at the center is the* CO_2 *storage geological underground formation.*

Pérez-López et al. (2018) carried out a first approach to the application of this methodology at Hontomín, under the objective of the ENOS project (see next section for further details). We propose a circular searching of structural field stations (**Figs. 4, 5**), located within a 20 km radius. This circle was taken given that active faults with the capacity of triggering earthquakes of magnitudes close to M 6, exhibits a surface rupture of tens of kilometers, according to the empirical models (Wells and Coppersmith, 1994). Moreover, Verdon et al. (2015) pointed out that the maximum distance of induced earthquakes for fluid injection is 20 km. Larger distances could not be related to the stress/strain regime within the reservoir, except for the case of large geological structures (folds, master faults, etc.). Microseismicity in CCS reservoir is mainly related to the operations during the injection/depletion stages and long-term storage (Verdon 2014, Verdon et al., 2015, McNamara, 2016).

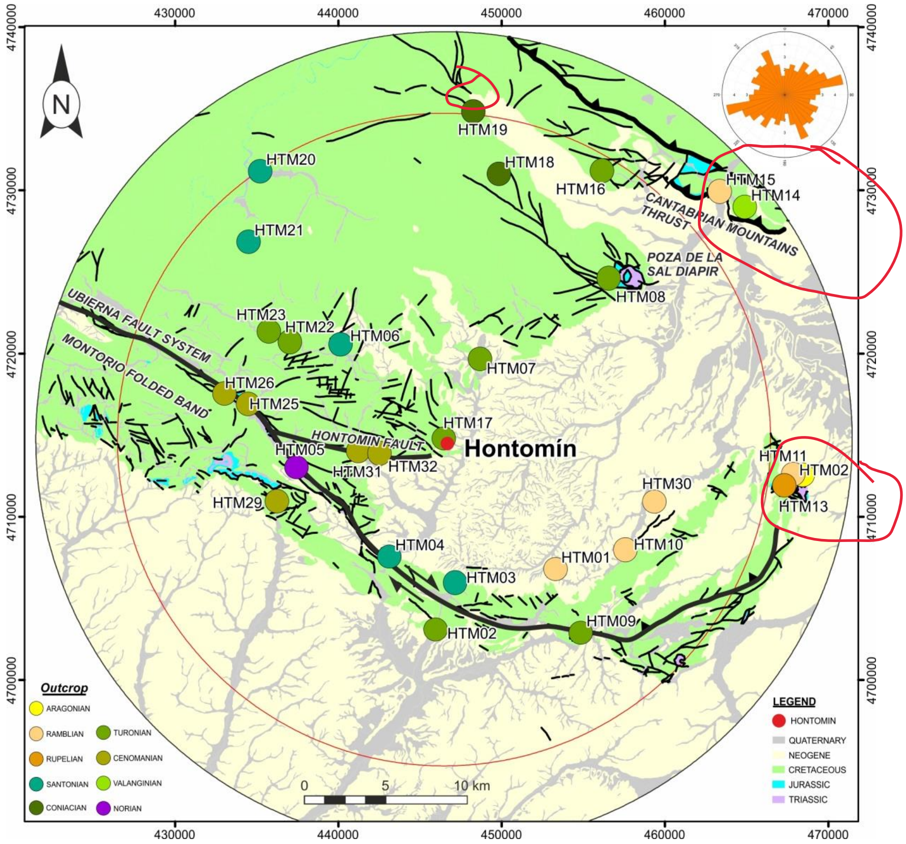


Figure 5. Geographical location of field outcrops in the eastern part of the Burgalesa Platform domain. Black lines: observed faults; red circle: 20km radius study zone. A total of 447 fault data were collected in 32 outcrops. Data were measured by a tectonic compass on fault planes at outcrops. The spatial distribution of the field stations is constrained by the lithology. Coordinates are in meters, UTM H30.

The presence of master faults (capable to trigger earthquakes of magnitude = or > than 6 and 5 km long segment) inside the 20 km radius circle, implicates that the regional tectonic field is relevant for the reservoir geodynamics, being responsible for the strain accumulation in kilometric fault-sized. Furthermore, the presence of master faults could increase the occurrence of micro-earthquakes, due to the presence of secondary faults prone to trigger earthquakes by their normal seismic cycle. ~~Bearing in mind that CCS onshore reservoirs use to be deep saline aquifers~~ (e.g. Bentham and Kirby, 2005), as Hontomín is (Gastine et al., 2017, Le Gallo and de Dios, 2018), and be related to folding and fractured deep geological structures, local tectonics plays a key role in micro-seismicity and the possibility of CO_2 leakage.

The constraints of this strategy are related to the absence of kinematics indicators on fault planes, due to the geomechanical property of the lithology involved or the erase by later geological processes as neoformed mineralization, etc. A poor spatial distribution of the outcrops was also taken into account for constraining the strategy. The age of sediments does not represent the age of the active deformations and hence, the active deformation has to be analyzed by performing alternative methods (i.e. paleoseismology, archaeoseismology).

4. RESULTS

4.1 Strain Field Analysis

We have collected 447 fault-slip data on fault planes in 32 outcrops, located within a 20 km radius circle centered at the HPP (**Fig. 5**). The age of the structural field stations ranges between Early Triassic to present-day and are mainly located in Cretaceous limestones and dolostones (**Fig. 5, Table 2**). No Jurassic outcrops were located, and seven stations are located on Neogene sediments, ranging between Early Oligocene to Middle-Late Miocene. The short number of Neogene stations is due to the mechanical properties of the affected sediments, mainly poor-lithified marls and soft-detrital fluvial deposits. Despite that, all the Neogene stations exhibit high-quality data with a number of fault-slip data ranging between 7 and 8, enough for a minimum quality analysis.

We have labeled the outcrops with the acronym HTM followed by a number (see **figure 5** for the geographical location and **Table 2** and **figure 6** for the fault data). The station with the highest number of faults measured is HTM17 with 107 faults on Cretaceous limestone. Nevertheless, we have removed the HTM17 to the analysis due to the high number of measurements, including lot of noise that could disturb the whole analysis. Conjugate fault systems can be recognized in most of the stations (HTM1, 3, 5, 7, 10, 14, 16, 21, 23, 25, 26, 29, 30 and 32, **Fig. 6**), although there are ~~a few~~ stations with only one well defined fault set (6, 22, 32). We have to bear in mind that recording of conjugate fault systems are more robust for the brittle analysis than recording isolated fault sets, better constraining the solution (Žaholar and Vrabec, 2008). In total, 29 of 32 stations were used (HTM24, 27, 28 with no quality data), and from these 29 stations, 24 were analyzed with the paleostrain technique. Solutions obtained here are robust to establish the strain field as the orientation of the e_y, S_{Hmax} (**Figs. 7** and **8**).

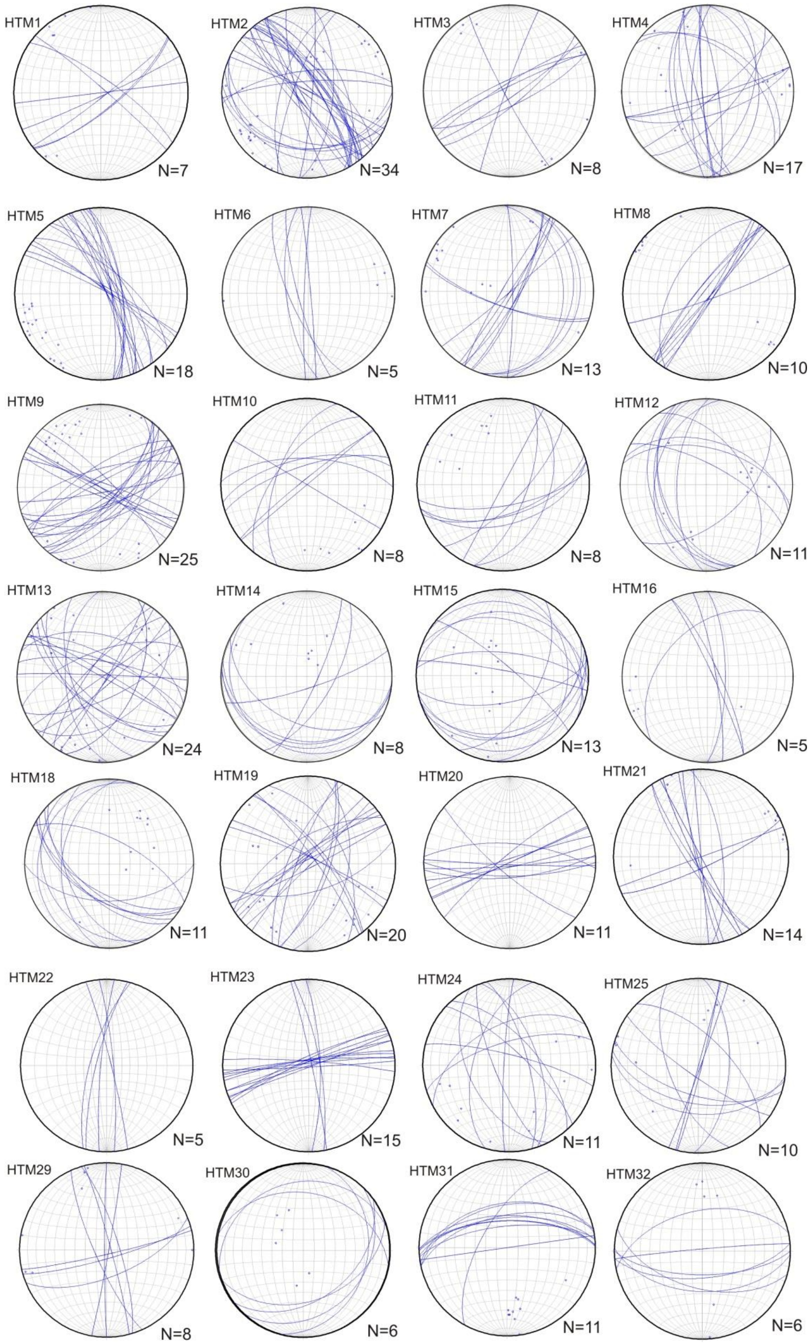


Figure 6. Stereographic representation (cyclographic plot in Schmidt net, lower hemisphere) of the fault planes measured in the field stations. "n" is the number of available data for each geoestructural station. HTM24, 27, 28 are not included due to lack of data, and HTM17 due to the high number of faults.

The results obtained from the application of the paleostrain method have been expressed in stereogram, right dihedral (RD), slip method (SM) and K'- diagram (**Fig. 7)**. The K'-diagram shows the fault classification as normal faults, normal with strike-slip component, pure strike-slip, strike-slip with reverse component and reverse faults (see **Fig. 3**). Main faults are lateral strike-slips and normal faults, followed by reverse faults, strike-slips and oblique strike-slips faults. The results of the strain regime are as follows: 1) 43% of extensional with shear component; 2) 22% of shear; 3) 13% of compressive strain (lower Cretaceous and early-middle Miocene, **Table 2**); 4)13% of pure shear and 5) 9% of shear with compression strain field, although with the presence of five reverse faults.

On the other hand, we can observe that there are solutions with a double value for the e_y, S_{Hmax} orientation: HTM1, 2, 10, 11, 13, 15, 19, 26, and 30. The stations HTM3 and 23 (upper Cretaceous), show the best solution for strike-slip strain field as a pure strike-slip regime and e_y with N25°E and N99ºE trend, respectively (**Fig. 7**).

It is easy to observe the agreement between the e_y results from the SM and the K'- strain diagram, for instance, in the HTM 2 the K'-diagram indicates strike-slip faults with reverse component for low dips ($0^o < \beta < 40^o$) but also indicates strike-slip faults with normal component for larger dips ($40^o < \beta < 90^o$). However, both results are in agreement with a strain field defined by the orientation for e_y, S_{Hmax} with N150º ± 18° trend. This tectonic field affects Cretaceous carbonates and coincides with the regional tectonic field proposed by Herraiz et al. (2000), Stich et al. (2006),Tavani et al. (2011) and Alcalde et al. (2014).

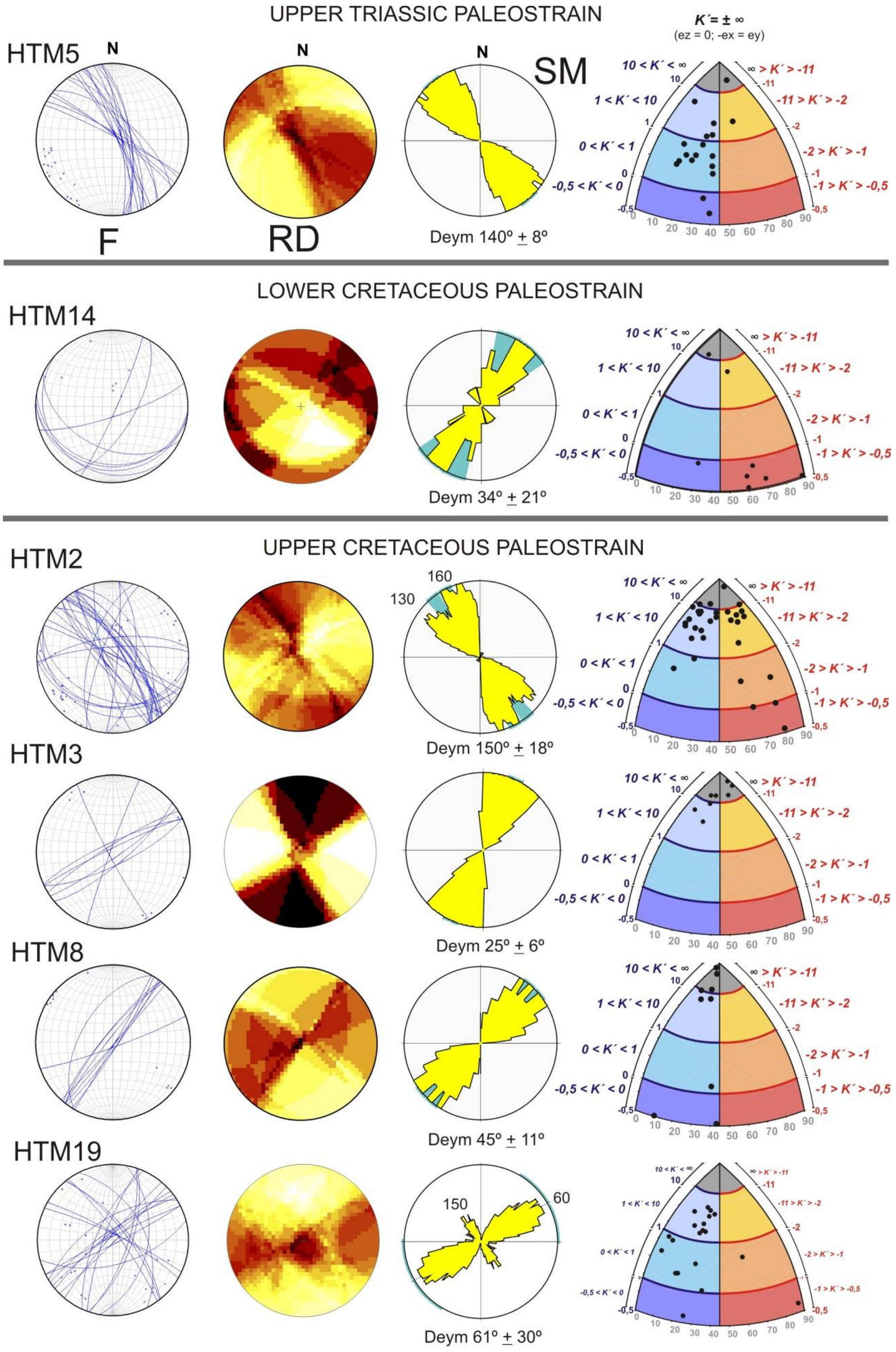

UPPER TRIASSIC PALEOSTRAIN
HTM5
N
F
RD
SM
Deym 140º ± 8º
K´= ± ∞
(ez = 0; -ex = ey)
10 < K´ < ∞
1 < K´ < 10
0 < K´ < 1
-0,5 < K´ < 0
∞ > K´ > -11
-11 > K´ > -2
-2 > K´ > -1
-1 > K´ > -0,5
10 20 30 40 50 60 70 80 90
LOWER CRETACEOUS PALEOSTRAIN
HTM14
Deym 34º ± 21º
UPPER CRETACEOUS PALEOSTRAIN
HTM2
160
130
Deym 150º ± 18º
HTM3
Deym 25º ± 6º
HTM8
Deym 45º ± 11º
HTM19
150
60
Deym 61º ± 30º

FIGURE 7a

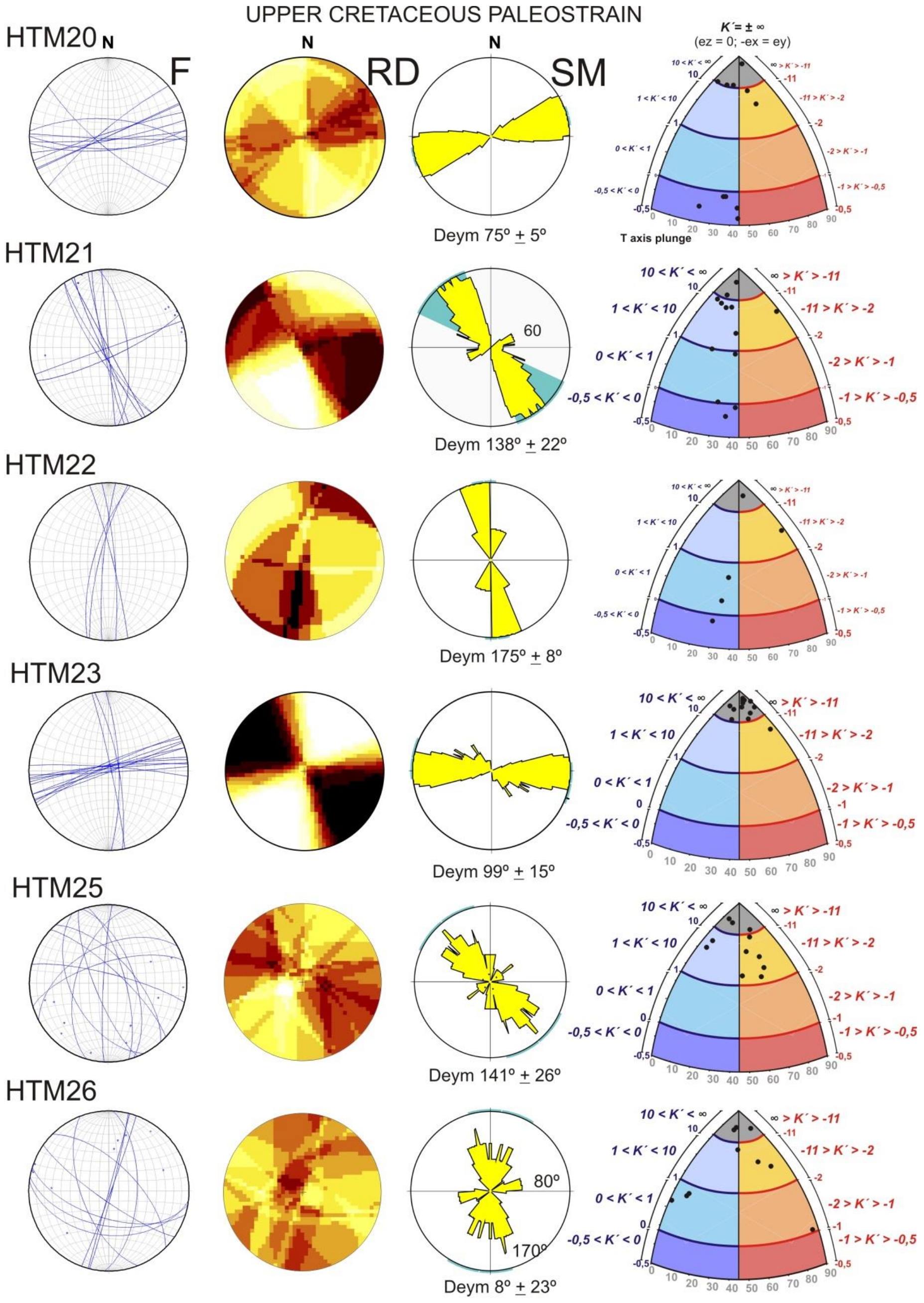

UPPER CRETACEOUS PALEOSTRAIN
HTM20
N
F
RD
SM
Deym 75º ± 5º
K´= ± ∞
(ez = 0; -ex = ey)
10 < K´ < ∞
1 < K´ < 10
0 < K´ < 1
-0,5 < K´ < 0
∞ > K´ > -11
-11 > K´ > -2
-2 > K´ > -1
-1 > K´ > -0,5
T axis plunge
0 10 20 30 40 50 60 70 80 90
HTM21
60
Deym 138º ± 22º
HTM22
Deym 175º ± 8º
HTM23
Deym 99º ± 15º
HTM25
Deym 141º ± 26º
HTM26
80º
170º
Deym 8º ± 23º

FIGURE 7b

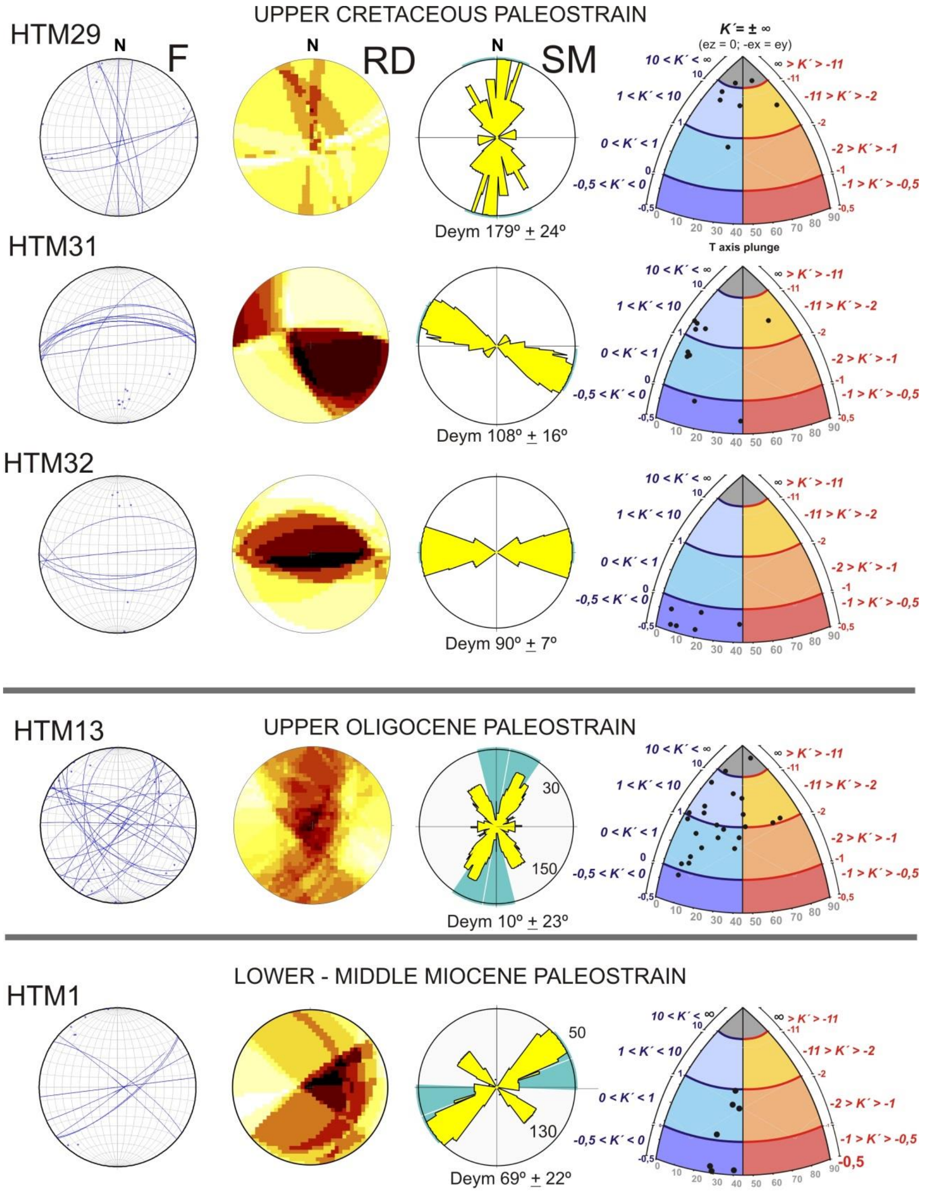

UPPER CRETACEOUS PALEOSTRAIN
HTM29
N
F
N
RD
N
SM
Deym 179º + 24º
K´= ± ∞
(ez = 0; -ex = ey)
10 < K´ < ∞
1 < K´ < 10
0 < K´ < 1
-0,5 < K´ < 0
∞ > K´ > -11
-11 > K´ > -2
-2 > K´ > -1
-1 > K´ > -0,5
10
1
0
-0,5
-11
-2
-1
-0,5
10 20 30 40 50 60 70 80 90
T axis plunge
HTM31
Deym 108º + 16º
HTM32
Deym 90º + 7º
UPPER OLIGOCENE PALEOSTRAIN
HTM13
30
150
Deym 10º + 23º
LOWER - MIDDLE MIOCENE PALEOSTRAIN
HTM1
50
130
Deym 69º + 22º

FIGURE 7c

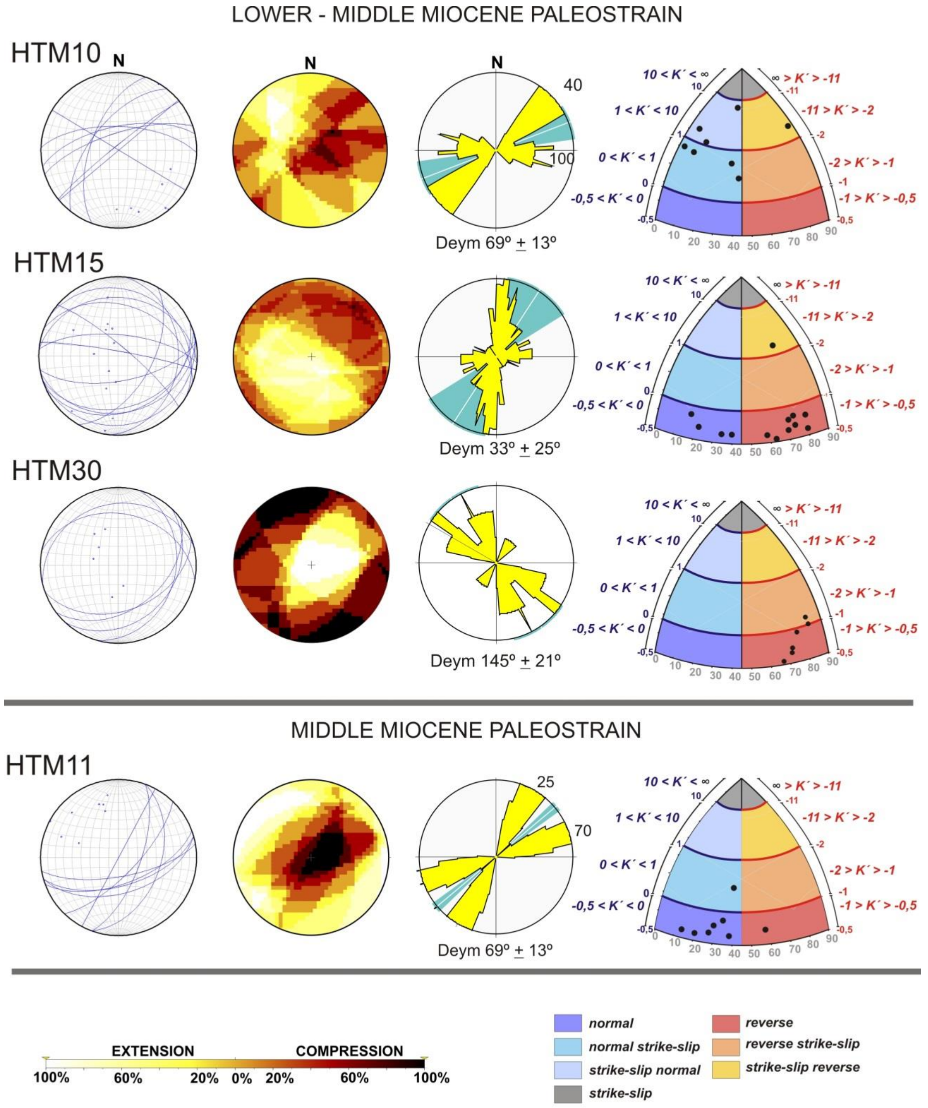
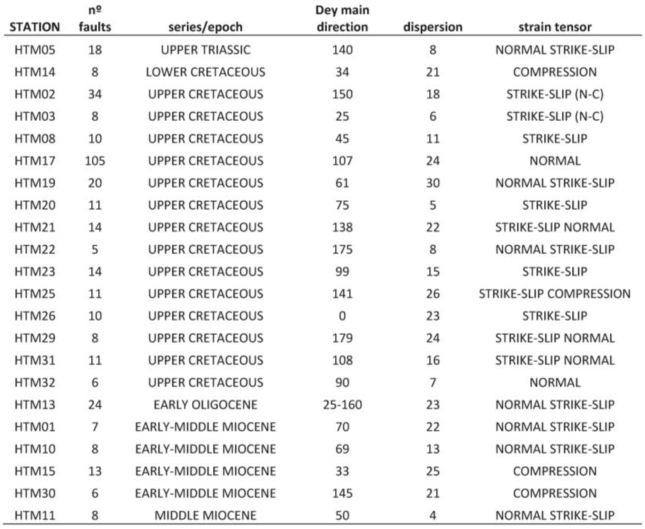


FIGURE 7d

Figure 7. Results of the paleostrain analysis obtained and classified by age. Deym: striking of the averaged of the De$_y$ *value; F: fault stereographic representation; K': diagram with dots for each fault slip solution; RD: Right Dihedral method; SM: Slip Method, K'. See Methods for further explanation.*



STATION	nº faults	series/epoch	Dey main direction	dispersion	strain tensor
HTM05	18	UPPER TRIASSIC	140	8	NORMAL STRIKE-SLIP
HTM14	8	LOWER CRETACEOUS	34	21	COMPRESSION
HTM02	34	UPPER CRETACEOUS	150	18	STRIKE-SLIP (N-C)
HTM03	8	UPPER CRETACEOUS	25	6	STRIKE-SLIP (N-C)
HTM08	10	UPPER CRETACEOUS	45	11	STRIKE-SLIP
HTM17	105	UPPER CRETACEOUS	107	24	NORMAL
HTM19	20	UPPER CRETACEOUS	61	30	NORMAL STRIKE-SLIP
HTM20	11	UPPER CRETACEOUS	75	5	STRIKE-SLIP
HTM21	14	UPPER CRETACEOUS	138	22	STRIKE-SLIP NORMAL
HTM22	5	UPPER CRETACEOUS	175	8	NORMAL STRIKE-SLIP
HTM23	14	UPPER CRETACEOUS	99	15	STRIKE-SLIP
HTM25	11	UPPER CRETACEOUS	141	26	STRIKE-SLIP COMPRESSION
HTM26	10	UPPER CRETACEOUS	0	23	STRIKE-SLIP
HTM29	8	UPPER CRETACEOUS	179	24	STRIKE-SLIP NORMAL
HTM31	11	UPPER CRETACEOUS	108	16	STRIKE-SLIP NORMAL
HTM32	6	UPPER CRETACEOUS	90	7	NORMAL
HTM13	24	EARLY OLIGOCENE	25-160	23	NORMAL STRIKE-SLIP
HTM01	7	EARLY-MIDDLE MIOCENE	70	22	NORMAL STRIKE-SLIP
HTM10	8	EARLY-MIDDLE MIOCENE	69	13	NORMAL STRIKE-SLIP
HTM15	13	EARLY-MIDDLE MIOCENE	33	25	COMPRESSION
HTM30	6	EARLY-MIDDLE MIOCENE	145	21	COMPRESSION
HTM11	8	MIDDLE MIOCENE	50	4	NORMAL STRIKE-SLIP

Table 2. Summary of the outcrops showing the number of faults, the type of the strain tensor obtained, the De_y, S_{Hmax} *striking and the age of the affected geological materials. Asterisk indicates those field stations detailed in the figure 7. N-C is normal component for strike-slip movement.*

Two e_y, S_{Hmax} directions can be considered, N150ºE and N50ºE. We obtained an averaged value of N105ºE by mixing both values of trend. However, a large number of measured faults and their uncertainties slightly disturb the results (**Table 2**).

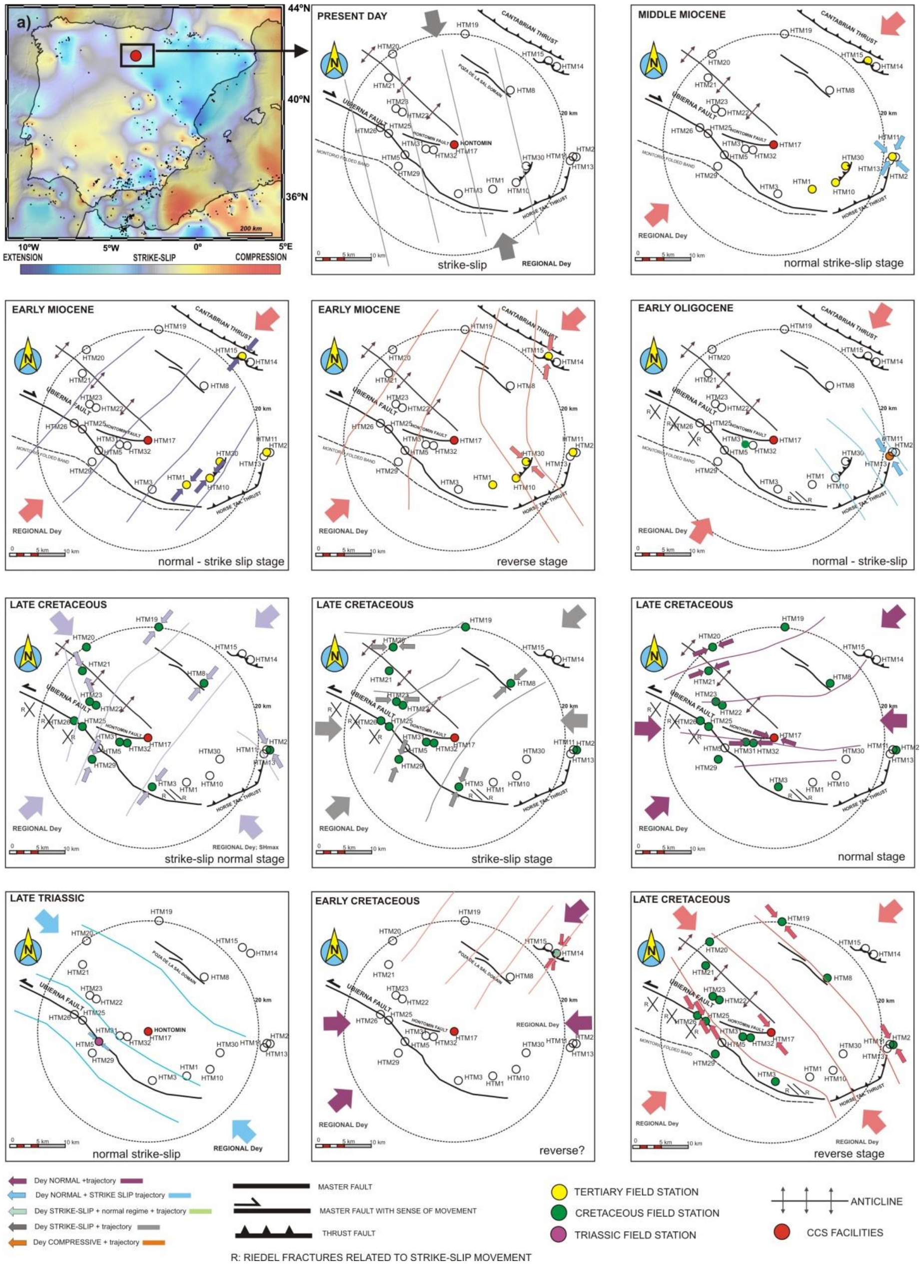


Figure 8) Upper left frame: Synthesis of the K'- map obtained from Giner-Robles et al. (2018) for the whole Iberian Peninsula from focal mechanism solutions. HPP is located between a triple junction of K' defined by compression towards the north, extension to the southeast and strike-slip to the west. Black dots are the earthquakes with focal mechanism solutions used. Sketches represent the e_y, S_{Hmax} trajectories obtained from the outcrops for early Triassic, Early Cretaceous, Late Cretaceous, Early

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Oligocene, Early – Middle Miocene and Present-day strain field from Herraiz et al. (2000). Main structures activated under the strain field defined are also included.

4.2 Late Triassic Paleostrain

Strain analysis from HTM5 fault set shows e_y with NW-SE trending and shear regime with extension defined by strike-slip faults (**Figs. 7a** and **8**). This is in agreement with the uniaxial extension described in Tavani (2012), author that constrain this regime with S_{hmin} with NE-SW trending.

4.3 Cretaceous Paleostrain

HTM 14 is the only outcrop from early Cretaceous age, showing a compressive tectonic stage with reverse fault solutions, defined by e_y with NE-SW trending (**Fig. 8**). Taking into account the extensional stage related to the Main Rifting Stage (i.e. Carola, 2004; Tavani, 2012; Tugend et al., 2014) during this age, we interpreted these results as a modern strain field, probably related to the Cenozoic Inversion stage. A local compressive stage was discarded due to the absence of compressive structures related to this age in the area and surroundings.

Outcrops HTM 2, 17, 19, 20, 21, 23, 25, 26, 29, 31 and 32 are from the upper Cretaceous carbonates, and four main strain fields are described, depending on the fault sets (**Fig. 8**): (1) a compressive stage featured by e_y with NW-SE trending, similar to those stage described in Tavani (2012), (2) a normal strain stage with e_y striking both E-W and NE-SW (**Fig. 8**, HTM 20, 21, 31 and 32). Finally, a (3) a shear stage (activated strike-slip faults) and (4) a shear with an extension (strike-slip with normal component) were described as well. These two late stages are featured by e_y with NE-SW and NW-SE trends. The existence of four different strain fields is determined by different ages during the Cretaceous and different spatial locations in relation to the main structures, the Ubierna Fault System, Hontomin Fault, Cantabrian Thrust, Montorio folded band and the anticline (**Fig. 8**).

4.4 Cenozoic strain field

The Cenozoic tectonic inversion was widely described in the area by different authors (e.g. Carola, 2004; Tavani, 2012; Tungend et al., 2014). This tectonic inversion is related to compressive structures, activating NW-SE and NE-SW thrusts with NW-SE and NNE-SSW e_y trends, respectively. The Ubierna Fault has been inverted with ~~a~~ right-lateral transpressive kinematics during the Cenozoic (Tavani et al., 2011). Early Oligocene outcrop (HTM13, **Figs. 7c** and **8**) shows an extensional field with e_y with NNE-SSW trending. During the Miocene, HTM15 and HTM30 outcrops exhibit the same e_y striking, but for compressive tectonic stage (**Figs. 7c** and **8**). In addition, during the middle Miocene, an extensional tectonic strain is described and characterized by NNE-SSW and NE-SW trends. Summarizing, the Cenozoic inversion and tectonic compression are detected during the early middle Miocene, later to the Oligocene, but during the middle Miocene, only one extensional stage was interpreted.

The outcrops located closer to the HPP (HTM 17, 31, 32, **Figs. 5 and 7**), show E-W faults. HTM05 is located on the Ubierna Fault, showing NW-SE, whilst HTM03 shows strike-slip NE-SW. Moreover, this station is located within a valley with the same orientation and surrounding faults have the same orientation (**Fig. 5**). Close to the HPP facilities, E-W faults are measured. This fault set was activated under a strain field defined by e_y with E-W trending and K'-diagram shows normal faults with strike-slip component. However, the present-day e_y with a roughly N-S trend (Herraiz et al., 2000, Stich et al., 2006), could active E-W faults as reverse faults and hence, more energy would needed to move like seismic sources. In addition, fault dip data obtained from structural analysis can be included in geomechanical analysis of fault rupture.

Strain analysis suggests that the planes that could affect the leakage into the reservoir would be those planes parallel to the S_{Hmax} orientation, that is, NNW-SSE and N-S (**Fig. 7**). Moreover, N50ºE S_{Hmax} orientation could also affect the reservoir. HPP facilities are close to WNW-ESE fault although the HTM17 station shows that N-S fault planes could play an important role for seepage fluid into the reservoir.

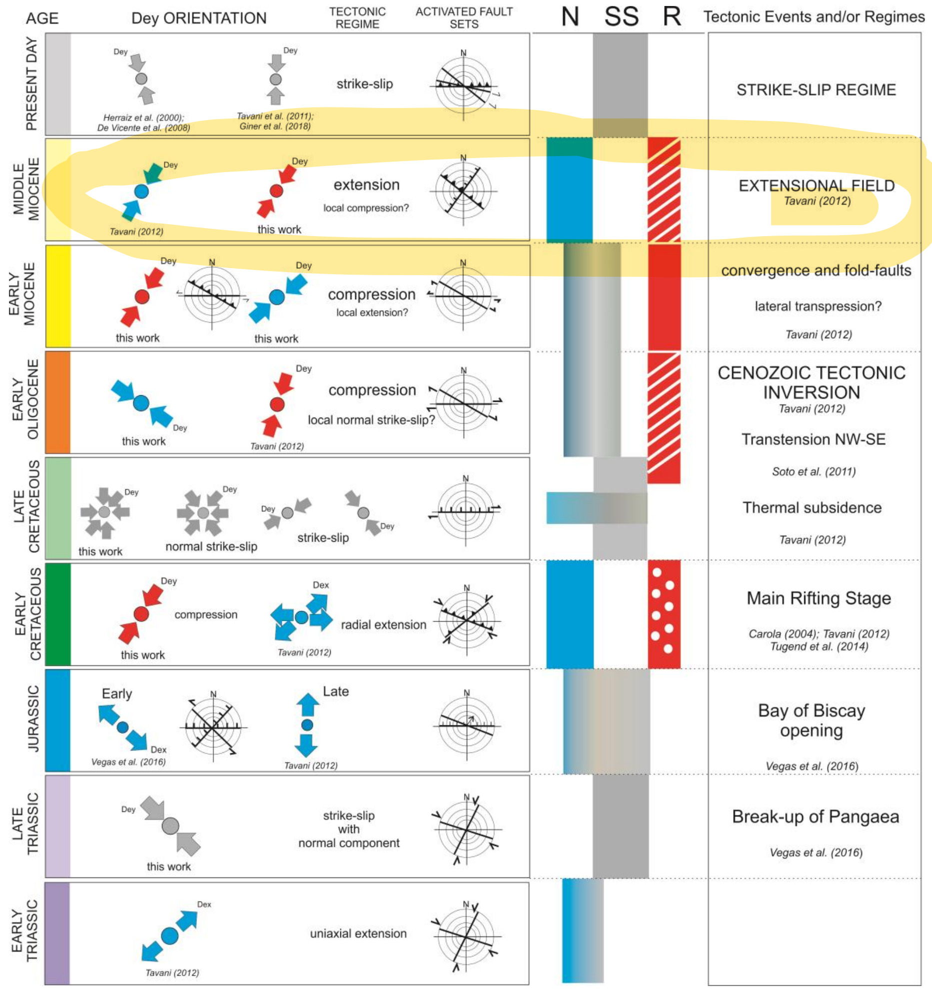

Figure 9. Tectonic field evolution of the Burgalesa Platform domain (20-km radius circle centered at HPP), interpreted from the paleostrain analysis. The regional tectonic field from other authors are also included. Ages were estimated from the HTM outcrops affecting geological well-dated deposits. N: extensional faulting; R: compressive faulting; SS: strike-slip faulting. Red and white means local paleostrain field, and red with white dots means superposed modern paleostrain field.

5. DISCUSSION

5.1. Mesozoic – Cenozoic Paleostrain evolution

We propose a tectonic field evolution for the Hontomín CCS area, from the Triassic to Neogene times (**Fig. 9**), based on the results obtained from the paleostrain analysis (**Fig. 8**). Furthermore, the data used in this work were completed from available bibliographic data of paleostress and paleostrain affectingn the Burgalesa Platform (see references in **Fig. 9**) and large-scale tectonic events.

Triassic age is featured by a uniaxial extension determined by a paleostrain field with e_x striking NE-SW (Tavani, 2012). The oldest tectonic strain field that we have obtained, recorded during the Late Triassic, is represented by a strike-slip tectonic field with shear component (**Figs 7a, 8** and **9**), which we have related with the break-up of Pangaea. In this stage, NE-SW right lateral faults are dominant.

No Jurassic outcrops are in the studied area and hence, the Jurassic deformation assumed in this work comes from Tavani (2012), suggesting the aperture of the Bay of Biscay in a large-scale N-S extension. Alcala et al. (2014) pointed out a tectonic evolution from Lias diparism (Early Jurassic) and N-S tectonic extension, activating E-W extensional faults. Moreover, Vegas et al. (2016) interpreted a rift extension during this period.

The Early Cretaceous tectonic field shows a e_y with NE-SW trend, determining a compressive and convergence local stage (**Figs 7a, 8**). However, we have assumed this strain field as modern, probably during the Cenozoic inversion, overlapping the extensional regional paleostrain (**Fig. 9**, red with white circles). The Upper Cretaceous tectonic strain is defined by several e_y trends, from an initial N-S and NE-SW, to NW-SE in a final transtensional state, which is in agreement with Soto et al. (2011), being active even during the Early Oligocene.

The tectonic convergence represented by a NE- trending S_{Hmax}, determining a reverse field to have taken place during the Early Miocene, although Tavani (2012) pointed out that the Cenozoic tectonic inversion could start at the Upper Cretaceous. During the Miocene, normal faults with shear during this period (**Fig. 9**) could be interpreted as folding fractures. In this case, extensional faulting could appear in the upper part of anticlines formed by bending. The middle Miocene is interpreted as an extensional stage with normal strain field.

Finally, the active strain field (Miocene-Present-day), shows a local compressional field with N50ºE trending e_y, S_{Hmax} with and the regional field with N150ºE trending e_y, S_{Hmax}. The active regional field proposed by Herraiz et al. (2000), Stich et al. (2006), Tavani et al. (2011) and Alcalde et al. (2014), shows e_y, S_{Hmax} with almost NNW-SSE and N-S trends.

5.2 Active faulting in the surrounding of HPP

Quaternary tectonic markers for the UFS are suggested by Tavani et al. (2011). According to the tectonic behavior of this fault as right-lateral strike-slip, and the fault segments proposed by Tavani et al. (2011), ranging between 12 and 14 km long, the question is whether this fault could trigger significant earthquakes and which could be the maximum associated magnitude. This is a relevant question given that the "natural seismicity" in the vicinity could affect the integrity of the caprock. Bearing in mind the expectable long-life for the reservoir, estimated in thousands of years, the potential natural earthquake that this master fault could trigger has to be estimated. In this sense, it is necessary to depict seismic scenarios related to large earthquake triggering; however, this type of analysis is beyond the focus of this work.

The income information that we have to manage in the area of influence (20 km) is: (a) the instrumental seismicity, (b) the geometry of the fault, (c) the total surface rupture, (d) the upper crust thickness and (e) the heat flow across the lithosphere. Starting for the heat flow value, the Hontomín wells show a value that lies between 62 and 78 mW/m^2 at a 1,500 m depth approximately (Fernández et al., 1998). Regarding the Moho depth in the area, these aforementioned authors obtained a value ranging between 36 and 40 km depth, while the lithosphere ranges between 120 and 130 km depth (Torne et al., 2015). The relevance of this value is the study of the thermal weakness into the lithosphere that could nucleate earthquakes in intraplate areas (Holford et al., 2011). For these authors, the comparison between the crustal heat-flow in particular zones, in contrast with the background regional value, could explain large seismicity and high rates of small earthquakes occurrence, as the case of the New Madrid seismic zone. For example, in Australia heat-flow values as much as 90 mW/m^2 are related with earthquakes $M > 5$.

Regarding the maximum expected earthquake into the zone, we have applied the empirical relationships obtained by Wells and Coppersmith (1994). We have used the equations for strike-slip earthquakes according to the strain field obtained in the area (pure shear), and the surface rupture segment for the Ubierna Fault System, assuming a surface rupture segments between 12 and 14 km (Tavani et al., 2011). The obtained results show that the maximum expected earthquake ranges between M 6.0 and M 6.1. Wells and Coppersmith (1994) indicate for these fault parameters a total area rupture ranging between 140 and 150 km^2. Surface fault traces rupture as lower as 7 km needs at least 20 km of depth in order to reach a value of the fault-area rupturing greater than 100 km^2, in line with a Moho between 36 and 40 in depth.

Regarding the instrumental earthquakes recorded into the area, the two largest earthquakes recorded correspond to magnitude M 3.4 and M 3.3, with a depth ranging between 8 and 11 km, respectively, and a felt macroseismic intensity of III (EMS98, www.ign.es, last access on May, 2019).Both earthquakes occurred between 50 and 60 km of distance from the Hontomín Pilot Plant. Only five earthquakes have been recorded within the 20-km radius area of influence and with small magnitudes ranging between M 1.5 and M 2.3. The interesting data is the depth of these earthquakes, ranging between 10 and 20 km, which suggest that the seismogenic crust could reach 20 km of depth.

Furthermore, if E-W sets act as extensional faults in this regional tectonic context, it would be related to the upper part of the no deformational compressive zone and reverse earthquakes would appear with the foci located deeper than 2 km. The strain field is directly related to the permeability tensor due to rock dissolution. Hence, this value could play an important role for long-term reservoir expected life.

5.3 Local tectonic field and Induced Seismicity

The fluid injection into a deep saline aquifer, which is used as CCS, generally increases the pore pressure. The increasing of the pore pressure migrates from the point of injection to the whole reservoir. Moreover, changes into the stress field for faults that are located below the reservoir, could also trigger induced earthquakes (Verdon et al., 2014). Nevertheless, to understand this possibility and the study the volumetric strain field spatial distribution is required (Lisle et al., 2009).

The injection of 10 k tons of CO_2 in Hontomín (Gastine et al., 2017) represents an approximate injected volume of CO_2 of 5.5 x10^6 m^3. The earthquake magnitude to this fluid-injected volume according to the McGarr (2014) and Verdon et al. (2014) could be M > 5 if there are faults with a minimum size of 10 km and oriented according to the present stress field within the influence area (N-S extensional faults and NE-SW/NW-SE strike slip faults). In the case of HPP, there are faults below the reservoir with this potential earthquake triggering (Alcalde et al., 2014). On the other hand, overpressure increasing the permeability of the carbonate reservoir along with the pore pressure variations of about 0.5 MPa, could trigger earthquakes, as well. Stress-drop related to fluid injections are also reported (Huang et al., 2016).

Le Gallo and de Dios (2018) described two main fault sets affecting the reservoir with N-S and E-W trend, respectively. According to the present-day stress tensor described by Herraiz et al. (2000) and Tavani et al. (2011), E-W fault-sets are accommodating horizontal shortening, which means that the permeability could be low, and N-S faults could act as strike-slip with trans-tensional component and, hence, higher permeability. On the other hand, increasing the pore-pressure of E-W faults could reduce de seismic cycle in these faults. Therefore, special attention has to be paid in microseismicity related to E-W faults. In this sense, the study of focal mechanisms solutions could improve the safety management, even for microearthquakes of magnitude lesser than M 3.

Moreover, the CO_2 lateral diffusion and pressure variation change during the fluid injection phase, and then the system would relax before to be increased during the next injection phase. In this context, the intermittent and episodic injection of CO_2 could also trigger earthquakes by the stress-field and fluid pressure variations in short time periods.

6. CONCLUSIONS

The application of the analysis for brittle deformation determines the tectonic evolution of the strain field, applied in Carbon Capture and Sequestration (CCS). The possibility that pore pressure variations due to fluid injection could change the stress/strain conditions in the reservoir's caprock, makes the study of the present-day tectonic field as mandatory for the storage safety operations. In this sense, we have to bear in mind that this kind of subsurface storage is designed for long-life expectancy, about thousands of years, and therefore, relevant earthquakes could occur affecting the sealing and the seepage of CO_2, compromising the integrity of the reservoir. Hence, we can conclude from our analysis the following items:

(1) The study of this tectonic field allows classifying the geometry of the faults to prevent prone earthquake-related structures and design monitoring seismic network.

(2) The influence area around the facilities of the CCS for studying the active stress/strain field could reach 20 km from the facility and the tectonic evolution of the geological history of the reservoir have to be established, adding missing information from map scale and boreholes. This information could be used from the 3D local fracture pattern estimation to avoid overpressure for increasing the permeability paths. Analysis of the stress-drop due to the fluid injection could be combined with this information to understand potential microseismicity associated with the injection operations.

(3) In the case of Hontomín Pilot-Plant, we have obtained two strain active tectonic fields featured as shear deformation. These fields are defined by (a) a local tectonic strain field with e_y, S_{Hmax} striking N50ºE and (b) the regional one defined by e_y, S_{Hmax} with N150ºE trend. In this context, strike-slip faults with NE-SW trend, reverse faults with NW-SE trend and reverse oblique faults oriented E-W, are accumulating present-

day tectonic deformation. Therefore, we propose the monitoring of E-W faults and the intersection with strike-slip faults, either due to the possibility to make high-permeable paths for CO_2 mobility, or due to the possibility to act as compressional faulting due to the increasing of the pore pressure during injection.

(4) Both WNW-ESE fault plus N-S and NE-SW directions are the preferential fault directions for potential fluid leakage. E-W could act as compressive faults.

(5) The Ubierna Fault System represents a tectonically active fault array that could trigger natural earthquakes as large as M 6 (±0.1), from the empirical relationship of the total rupture segment (ranging between 12 and 14 km, and the total fault-area rupture, oscillating between 100 and 150 km^2). Despite the lack of instrumental seismicity into the influence area, we cannot obviate the potential earthquake occurrence within intraplate areas due to the long- timescale expected-life of the CCS. The heat-flow values and thermal crust conditions could determine the presence of intraplate earthquakes with magnitude $M > 5$, for a long timescale (thousands of years).

The tectonic evolution and kinematics of the west part of the Burgalesa Platform domain from upper Triassic to present day show a Cretaceous tectonic inversion, local reverse strain field during the early Oligocene and early Miocene, with a Normal strain field during the middle Miocene. The active strain field is now defined by a shear tectonic defined by e_y with N-S trend, activating E-W thrust and right-lateral faults with WNW- and NW- trend.

Finally, we state that the determination of the active tectonic strain field, the recognition and study of active faults within the area of influence (20 km), the estimation of the maximum potential triggered natural earthquake, the modeling of the stress-change during the fluid injection and stress-drop, probably improve the operations for a secure storage. In a short future, earthquake scenarios will be the next step: modeling the

Coulomb static stress-changes due to fluid injection and the modeling of intensity maps of horizontal seismic acceleration.

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