Dear Editor,

We have revised our original manuscript titled: “Active tectonic field for CO_2 Storage management: Hontomín onshore study-case (SPAIN)”, by Pérez-López et al., according to the revisions suggested by Pr. Graham Yielding and an anonymous reviewer (AR2) under the Open Discussion of Solid Earth.

We thank both reviewers their generous contribution. Firstly, we have revised Mr. Yielding’s comments because this revision was more complex. Secondly, the anonymous AR2 comments were also faced. Definitively, both remarks have improved the original manuscript and focused the main goal, the study of the active tectonics applied in CO_2 storage, on the text. We hope that this revision response enough both reviewers and the SE editor. Both reviewers are thanked for their opportune and successful contributions.

The authors, March, 2020.

P.S. We have detected some minor mistakes and typos not noted by the reviewers that we have removed.

Answers step-by-step:

Dear Dr. Yielding,

Thank you very much for your time and effort in reviewing the manuscript under the open discussion of Solid Earth and your kind comments. You pointed accurately the main objective of the paper, “the reactivation of faults due to the injection of fluids and the potential for triggering earthquakes, within the vicinity of the CCS (Carbon Capture and Storage), and pilot plant facilities”. According to the suggestion of anonymous reviewer #2, hereafter we refer to Geological Storage of CO_2 (GSC) instead of CCS.

We agree with you that the main goal of the paper was not the paleostrain evolution and global tectonic events recognized in the Basque-Cantabrian area and Duero and Ebro river basins (North part of Spain), but the role of the fault sets affecting the GSC by the present-day strain field. The high-quality outcrops in the near-field (<20 km) gave us a good chance to estimate different paleostrain local tensors affecting geological formations at different ages.

On the other hand, the controversy related to the assignment of geological ages to the different strain tensors calculated in geological outcrop is still an open debate. We well-know the problems to reconstruct paleostrain fields and how to match these results with large-scale tectonic events throughout the geological evolution of a geological basin. Of course, stress/strain axis rotations due to different paleogeographic constrains, magnetic field changes, among others, obviously difficult that reconstruction. As a matter of fact, the paleostrain reconstruction is always controversial, more if you take into account that all of our study is restricted to the local scale. This kind of analysis is always constrained by the quality of the outcrop and the ability to assign strain tensors to large-scale tectonic events affecting the studied area. We have indeed tried to match the paleostrain tensors calculated from slip fault data with those global tectonic events defined by other authors in the area. Perhaps, we have failed to suggest that this is only a local analysis.

Consequently, we accept to remove the paleostrain evolution from the manuscript. Instead, we have included the Mohr-Coulomb failure criterion applied to the fault pattern affecting the outcrop located in the Hontomín Pilot Plant (subsection 5.1 within the section 5. Discussion). Therefore, original figure 8 and figure 9 were removed and new figures were included: Figs. 8, 9, 10 and 11.

Ancient Fig. 8 (**REMOVED**): 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 ey, S_{Hmax} trajectories obtained from the outcrops for early Triassic, Early Cretaceous, Late Cretaceous, Early 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.

Ancient Fig. 9 (**REMOVED**): Tectonic field evolution of the Burgalesa Platform domain (20-km radius circle centred 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.

Concerning the inclusion of the fault-slip data from the outcrop HTM17, as suggested by Dr. Yielding, we have incorporated a new section. At the beginning of this work, it was a long discussion among the authors about the convenience either to describe this outcrop, having in mind the relevance of the site-effects, or to remove this outcrop from the huge amount of information we had to deal with. We have included the section 4.4 Cretaceous Outcrop HTM17 on the Hontomín Pilot Plant and several new figures.

New Figs. 8 and 9: Results of the paleostrain analysis of HTM17

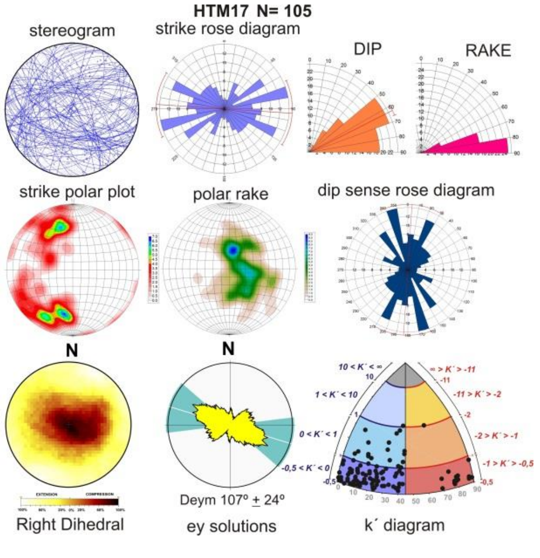

FIGURE 8

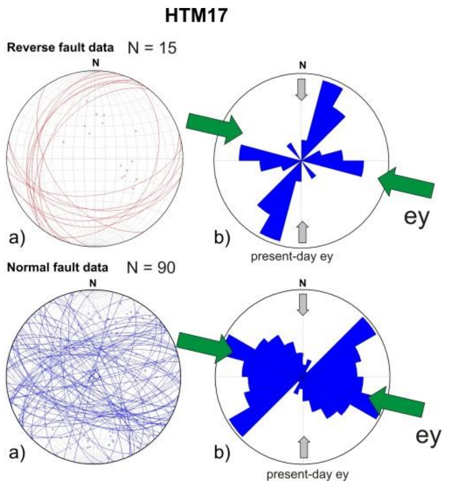

FIGURE 9

New Fig. 8. Fault data from the outcrop HTM17 located on top of the HPP. See figure 5 for the geographical location. Stereogram plot is lower hemisphere and Schmidt net.

New Fig. 9. Normal and reverse faults stereograms (lower hemisphere and Schmidt net), and rose diagrams measured in HTM17. Green arrows indicate the orientation of the local paleostrain field. Grey arrows indicate the orientation of the present-day regional stress field (Herraiz et al., 2000).

Besides, we have calculated how the present-day stress tensor affects to each strain tensor solution and fault sets as Yielding' suggestion. (Figure 10, Mohr-Coulomb failure criterion).

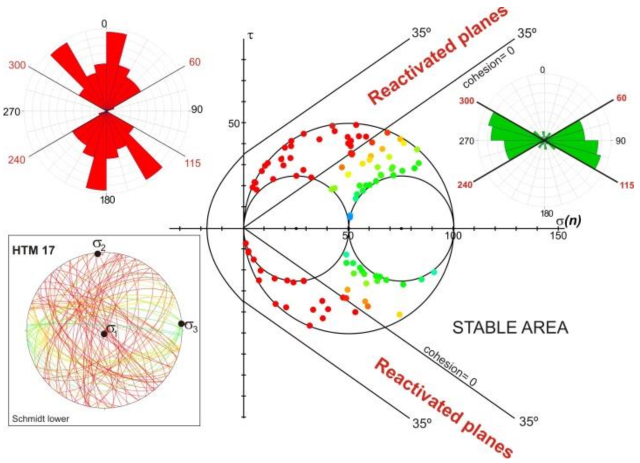

Figure 10. Mohr-Coulomb failure analysis for the fault-slip data measured in HTM17 under the present-day stress tensor determined by Herraiz et al. (2000). Red dots are faults reactivated, and green and orange dots are located within the stable zone. Red rose diagram shows the orientation of reactivated faults, between N-S to N60°E and from N115°E to N180°E. Green rose diagram shows the fault orientation for faults non-reactivated under the active tress field within the area. See text for further details.

Some sentences were modified from the abstract, introduction and other sections of the manuscript, concerning that HTM17 was not included here.

Finally, we don't agree with Dr. Yielding with the idea concerning the document has to be drastically rewritten. It is true that we have to include a new section describing the HTM17 outcrop and two new figures with the main data, and it is true again that we have rearranged the discussion section, by including the Mohr-Coulomb failure analysis applied to the HTM17 fracture pattern. However, the main analysis and focus of the manuscript is the same.

Nevertheless, we would like to thank to Pr. Yielding for putting the focus of our manuscript in the fault reactivation under fluid injection in GCE storage. We were some naïve to include a more complex analysis like the paleostrain reconstruction and matching with major tectonic events.

Thank you very much for your kind comments, revisions, and suggestions, that were properly focused on the aim of the manuscript, the role of the present-day strain field for GSC operations, and which definitively will improve the final manuscript.

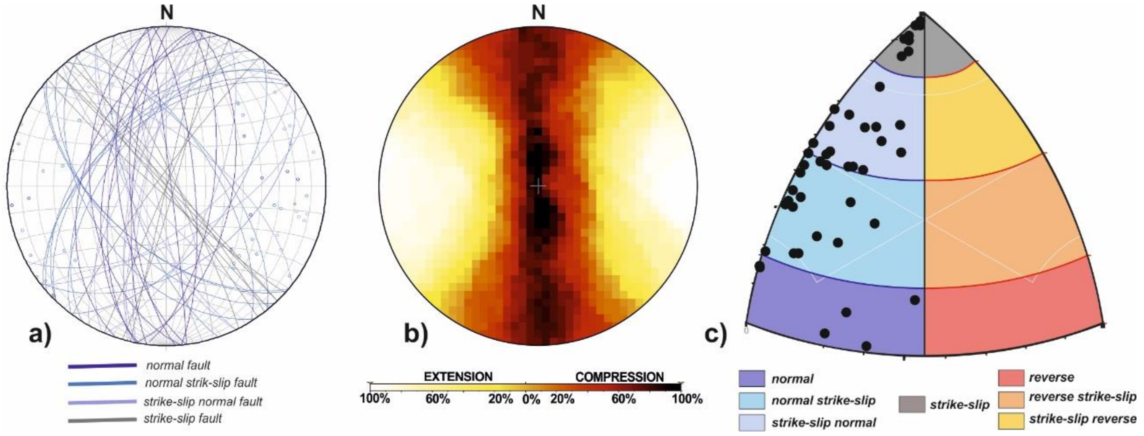

Figure 11. a) Stereogram and poles of fault sets (HTM17) reactivated under the present-day stress field suggested by Herraiz et al. (2000). b) Right-Dihedral of the reactivated fault sets. c) K'-strain diagram showing the type of fault for each fault-set.

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Answer to Anonymous referee #2 (AR2) related to the interactive comment on “Active tectonic field for CO_2 storage management: Hontomín onshore study-case (SPAIN)” by Pérez-López et al.

The authors (March, 2020)

First of all, thank you very much for your time and your effort, and for the constructive review of our work. We really feel that an open discussion improves the scientific results and we are willing to deal with it.

As detailed below, we answer all the points kindly provided by the Anonymous Referee #2 (hereafter AR2), in the same order he did.

We didn't analyze the past and present “stress” fields, we have analyzed the past and present “strain” fields. Although the orientations of both fields are similar, it is important to highlight the difference in terminology and concept between stress and strain. We have calculated strains. The Right Dihedral based on fault slip data yield “strain” and “paleostrain” fields. It is assumed that in the general case for the Anderson fault model, ey (the trajectory of maximum strain) is parallel to S_{Hmax} (maximum horizontal shortening) being different terms although (e.g. Giner-Robles et al. 2009). Therefore, the term strain is well used across the manuscript.

Our results do not evaluate “the risk” for leakage of CO_2 injection neither the possibility of triggering a M5 earthquake as AR2 suggests. RISK is a term that includes HAZARD plus VULNERABILITY plus EXPOSITION, and in our manuscript, we didn’t calculate that. In our conclusions, we expose the fault sets and orientation according to the present-day stress orientation which are affecting the caprock and the vicinity. We also describe a low-cost methodology to obtain paleostrain data, fault sets and their relationship with the present-day stress field, and we suggest including this kind of low-cost analyses for long-term geological CO_2 storage (GSC).

On the other hand (**we have removed this expression from the manuscript obeying the suggestion of AR2**), for estimating the potential seismic triggering of active faults, more analyses have to be carried out, for example, the study of active faulting by tectonic geomorphology and paleoseismology (see McCalpin 1996 and Papanikolaou et al. 2016, for instance). Therefore, the risk assessment for leakage of CO_2 is out of the scope of our manuscript.

Comment 1a. AR2 said that the analysis we made is common in monitoring strategies for GSC management. We don’t know any work about “strain inversion techniques” applied in GSC management so far. All the references suggested by AR2 are devoted to induced seismicity and the tectonic role in GSC management. We do not claim that we are pioneers in induced seismicity and tectonic studies on GSC. We simply present how the Structural Analysis of fault/slip data can improve the knowledge of the tectonic large-scale fault network for the potential seismic reactivation during fluid injection and time-depend scale for fluid stays. We have reinforced this idea by including this sentence at the end of the introduction section.

Comment 1b. **In this point, we agree with AR2** regarding the terminology about Carbon Capture and Storage (CCS), geological storage even Carbon sequestration (discarded terminology that we have used in the conclusion section). Hence, we will use only one. We agree with the term of geological CO_2 storage (GSC) and therefore, **we have changed CCS (carbon capture and storage, and other some former term which was included in the manuscript and removed for the revised version) for the term GSC**.

Comment 1c. Once again, the "*risk assessment*" was not performed in our work. This confusion is relevant to solve, it could lead to major mistakes for managing GSC. We insist that we have not carried out any kind of "risk analysis".

On the other hand, the expression used by AR2: "extremely unlike", to describe the potential of triggering M5 earthquakes by active faults near the GSC is not relevant to determine the real seismic hazard. There is no formal reference to this sentence and therefore we have ignored it.

We have applied a physic model to estimate the total volume injected (yes, we did it in room conditions), from the official data (referenced in the manuscript), and then we have applied the McGarr's (2014) approximation. Taking into account the uncertainties, our analysis "*should not be regarded as an absolute physical limit*", paraphrasing McGarr (2014)' words (page 1, ending sentence of the abstract section). According to McGarr (2014), the utility of the analysis that we have performed is "to predict in advance of a planned injection whether there will be induced seismicity", and in the case of the Hontomín Pilot Plant, by the estimation of the "total injected volume" in a small-scale injection plant (yes, the utility of a small injection plant, as pointed out by Cook et al., 2014).

McGarr (2014) applied his approach for three cases: (1) wastewater injection, (2) hydraulic fracturing, and (3) geothermal injection. We have gone one step beyond by including geological storage of CO_2. We assume that the pore pressure increases from CO_2 injection, in a similar way that wastewater does (originally defined by Frohlich, 2012). **We have included this paragraph in the revised manuscript**.

Regarding **Lines 673 and 674**: **We agree with AR2** that we have calculated the volume in "room conditions" for estimating the total injected volume, but we disagree with AR2 that it is a wrong estimation. We have read the work from McGarr (2014), and we did not found a reference that the injected value for the McGarr equation (eq 13) should be in "reservoir conditions". That means that our volume estimation was correct, and simply we have included "room conditions".

Regarding the calculation of the maximum seismic moment Mo(max), originated by the total injected fluid, we included the next paragraph:

We have applied a physic model to estimate the total volume injected (room conditions), and then we have applied the McGarr's (2014) approximation. The injection of 10 k tons of CO_2 *in Hontomín (Gastine et al., 2017), represents an approximated injected volume of* CO_2 *of* $5.56 \times 10^6\ m^3$ *(room conditions). We have used the expression Mo(max) (Nm) =* $G \cdot \Delta V$ *(McGarr 2014, eq. 13), where G is the modulus of rigidity and for the upper limit is* 3×10^{10} *Pa, and* ΔV *is the* *total injected volume (in room conditions). The result is Mo(max) equal to 1.67 x* 10^{17} *Nm (Joules), which corresponds to a maximum seismic moment magnitude Mw (max) = 5.45, by applying the equation Mw = (Log Mo(max) – 9.05)/1.5 from Hanks and Kanamori (1979); where Log is the logarithm to the base 10.*

We agree with AR2 that we have to include this calculation in the revised manuscript. Also, **it was a misprint of the result, the correct number is Mw= 5.45 instead of M= 6.01, by using the seismic moment magnitude instead of the Richter Magnitude. We have solved this and give thanks to AR2 for reviewing the math operations.**

Regarding the Ubierna Fault System (UFS), we simply claim that it is necessary to know the seismic cycle of their active segments to know the possibility that small induced seismicity could trigger a natural earthquake by changing the strain conditions. Today, that question is not well-known but as a matter of fact, the study of the strain fields by inversion techniques and the relationships with the active faults in the vicinity is a good approach to get a realistic answer. Up to now, there is not a known model or work analyzing the seismic cycle of the UFS. Our statement about the paleostrain and present-day strain analysis is a suggestion for best practice in the long term geological storage, not a fact. Regarding the "seismic cycle" and missing references, we have included Scholz (2018), one of the most general explanations of a wide-used description of active faults and related references.

Comment 2. AR2 asked a statistical analysis to the fault dataset but the Fault Population analysis in Structural Geology is a statistical analysis itself, so we did it. Perhaps AR2 means a calculation of uncertainties from age outcrops associated with quality parameters measured on the field. In this sense, we do not find any quality differences between the faults striations measured on fault planes. Any field data with doubt or potential misinterpretation from the field data was directly obviated to avoid biased results. Only high-quality striations and fibers were measured (see annexed figure 1). Moreover, geological ages mapped in the outcrops are enough constrained to be homogenous for the paleostrain reconstructions.

Comment 3. Thank you very much for your time and your effort to improve our English style, although we are not pretty sure that all of your suggestions are correct. Anyway, all of your suggestions will be revised and included if so. As a non-native English speaker, we always use professional aid. Bearing in mind that the manuscript was written by three different authors and finally homogenized by the first one, the English style could oscillate in different parts of the text. Thanks indeed.

Minor comments in the supplementary doc: (Major questions, English grammar questions are no answered here). In total, 17 questions were faced and answered. Line number is for the annotated text of the supplementary doc by the reviewer.

Q1 (abstract). AR2 asks about the "tectonic parameters": They are those parameters which characterize the tectonic field and framework: stress/strain parameters like S_{Hmax}, ey, k', R, natural heat-flow, Moho depth, crustal thickness, etc. In this case, the stress/strain ellipsoid and strain trajectories, master faults, tectonic slip rates, were showed in our work. **WE HAVE INCLUDED THIS SENTENCE.**

Q2 (abstract). Did In Salah (Algeria) case analyze the "*tectonic strain field*"? Please give us a reference.

Q3 (abstract). The reviewer confuses **stress** with **strain** again. They could be related in space, but are different concepts, as we said before. (see comment 1c.)

Q4 (page3). Ancient literature does not mean outdated literature. Please, indicate more appropriate literature if so related to the first stages of GSC and why Pearce 2006 is obsolete.

Q5 (Line74). What do you mean by long-term monitoring? We are meaning about the expected life of the reservoir in geological terms, from hundreds to thousand years.

Q6 (Line92). Geomechanical models related to the active tectonic field is not the aim of the paper and is out of the scope.

Q7. The election of 20 km for the strain analysis from geological outcrops is well explained. (3. Method and Rationale, section 3.5).

Q8 (Line110). Ok, removed.

Q9 (Line113). Why should we indicate that Hontomín is a pilot plant before the geological framework? We don't know any reason to prioritize this. Geology is the key for underground storage.

Q10 (**Line211**). **Geomorphic markers (misfit)**.

Q11 (Fig. 5). Some outcrops are close to 20 km but not exactly. Well, despite we use a GPS in the field, some outcrops were slightly out of 20 km but quite close to have influence in the geological map. We checked if outcrops were located about 20 km but not exactly. This is another reason to include the outcrops in a geological map.

Q12 (Line449). We strongly disagree. The tectonic field is relevant and their expressions are the master faults, they accommodate all of the deformations that it generates. The tectonic field and master faults are not independent concepts.

Line 592. Reference misprint removed (Alcalde et al., 2014.).

Line 631-640. One of the tectonic parameter to be considered is the crustal heat flow (see Q1). The relevance of this paragraph is to highlight that within intraplate areas large earthquakes could appear.

Line 643. Both strain fields.

Line 691. The use of focal mechanism solutions is crucial for understanding the failure mechanism in seismic prone areas. This information is world-wide used for the study of seismogenic faulting, modeling, earthquake hazard, seismic wave propagation, design of the seismic network, etc.

Line 693-696. Well, one thing is the permeability and lateral diffusion due to a single injection, and another thing is the mechanical behavior of the caprock under episodic injections. Both things have to be considered.

Minor remarks like the use of cap letters in Induced Seismicity and minor English grammar suggestions have been included in the revised manuscript.

NEW REFERENCES

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

Raúl Pérez-López[1], José F. Mediato[1], Miguel A. Rodríguez-Pascua[1], Jorge L. Giner-Robles[2], ~~Adriá~~ Adrià Ramos[1], Silvia Martín-Velázquez[3], Roberto Martínez-Orío[1], Paula Fernández-Canteli[1]

1. IGME – Instituto Geológico y Minero de España – Geological Survey of Spain. C/Ríos Rosas 23, Madrid 28003 – SPAIN. Email: r.perez@igme.es, jf.mediato@igme.es, ma.rodriguez@igme.es, a.ramos@igme.es, ro.martinez@igme.es, paula.canteli@igme.es
2. Departamento de Geología y Geoquímica. Facultad de Ciencias. Universidad Autónoma de Madrid. Campus Cantoblanco, Madrid. SPAIN. Email: jorge.giner@uam.es
3. Universidad Rey Juan Carlos. Email: silvia.martin@urjc.es

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Abstract

One of the concerns of underground CO_2 onshore storage is the triggering of Induced Seismicity and fault reactivation by pore pressure increasing. 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 statistical analysis of individual strain tensor solutions obtained from fresh outcrops from Triassic to Miocene. 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 about 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 kinematics fault analysis. The results indicate a strike-slip tectonic regime with the maximum horizontal shortening with N160°E and N50ºE trend for local regime, which activates NE-SW strike-slip faults~~ and NE-SW compressional faults~~. A regional extensional tectonic field was also recognized with N-S trend, which activates ~~E~~N-~~W ~~S ~~compressional ~~extensional faults, and NNE-SSW ~~plus~~and NNW-SSE strike-slip faults~~s~~, measured in the Cretaceous limestone on top of the Hotom~~i~~ín facilities. Monitoring ~~of~~ ~~E-W~~these faults within the reservoir is suggested in addition with the possibility of obtaining focal mechanism solutions for micro earthquakes (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. The Geological Carbon Storage (GSC)~~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 ~~GSC (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 earthquakes triggering, with the consequence of leakage and seepage, and (2) the long-term reservoir behavior, understanding as long-term from centennial to millennial time-span. Therefore, what is the long-term behavior of ~~CCS~~GSC? What do we need to monitor for a safe ~~CCS~~ GSC 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~~ GSC 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 large~~r~~ as M 1.7, detected in swarms about 9,500 microearthquakes, are related to ~~CCS~~ GSC operations. Additionally, Foulger et al. (2018) pointed out that ~~CCS~~ GSC can trigger earthquakes with magnitudes lesser than M 2, namely the cases described in their work are as great~~er~~ as M 1.8, with the epicenter location 2 km around the facilities. McNamara (2016) described a comprehensive method and protocol for monitoring ~~CCS~~ GSC 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~~ of 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~~ GSC 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) analysis between 20 away from the subsurface reservoir deep geometry, under the area of influence of induced seismicity for fluid injection. The knowledge of the strain field at local scale allows ~~to classify~~classifying the type of faulting and their role for leakage processes, whilst the regional scale explores the tectonic active ~~faults which~~faults that 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 directly classification of all the faults involved into the geomechanical model and the prediction of the failure parameters. Besides, a Mohr-Coulomb failure analysis was performed to the fault pattern recognized in the Cretaceous outcrop located on top of the pilot plant.

The tectonic characterization of the ~~CCS~~ GSC 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 analysis ~~protocol~~ to manage underground storage operations. We present how the Structural Analysis of fault/slip data can improve the knowledge of the tectonic large-scale fault network for the potential seismic reactivation during fluid injection and time-depend scale for fluid stays.

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 (Dallmeyer and Martínez-García, 1990; 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; Le Pichon and Sibuet, 1971; Lepvrier and Martínez-García, 1990; 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 Mesozoic extensional faults and the development of ~~a~~an E-W orogenic belt (Cantabrian domain to the west and Pyrenean domain to the east) formed along the northern Iberian plate margin (Muñoz, 1992; Gómez et al., 2002; ~~Muñoz, 1992;~~ Vergés et al., 2002).

The Hontomín facilities are located within the Basque-Cantabrian Basin (**Fig. 1b**). The geological reservoir 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 is defined as a forced fold related dome structure (Tavani et al., 2013; Fig. 2), 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 the Alpine Orogeny affecting the Pyrenees, the right-lateral transpressive inversion of the basement faults was activated, along with the reactivation of transverse extensional faults (Fig. 2; Tavani et al., 2013; Alcalde et al., 2014).

~~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 it is 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).~~

~~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, t~~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~~ ~~act~~acts as 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 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 tectonic 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 tectonic regime ~~within 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. ~~,~~ N~~n~~evertheless, local tectonics could determine the low permeability and the potential ~~Induced~~ induced ~~Seismicity~~ 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~~ The 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~~ GSC managing in the frame of geological risk, is based on the strain tensor calculation, as part of the objectives proposed in the European project "ENabling Onshore CO2 Storage in Europe" (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~~ GSC 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~~ GSC 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.~~

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 (dip~~.~~/ ~~D~~ dip direction and rake), 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. Finally, we have studied the fault plane reactivation by using the Mohr-

Coulomb failure criterion (Pan et al., 2016), from the fault pattern obtained in the ~~c~~Cretaceous limestone outcrop located on top of the HPP facilities.

~~2~~3.1 *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:

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

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

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~~ defines 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 dip values lower than 45º~~such as for compressional faulting values lower than b < 45º~~, 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 ~~D~~e_y SM results.

Resolving the equations of Anderson ~~(Anderson, 1951)~~ for different values (Anderson, 1951), we can classify the tectonic regime that activates one fault from the measurement of the fault dip, sense of dip (0º-360º) and pitch of the slickenside, assuming that one of the principal axes (e_x, e_y or e_z) ~~are~~ is 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 (β > 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 (Kaverina et al., 1996). 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 earthquake magnitudes 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.

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.

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~~ GSC reservoir, which will allow ~~for~~ the long-term monitoring ~~long-term~~of the geological and seismic behavior (Fig. 4). 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.

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~~ GSC reservoir is mainly related to the operations during the injection/depletion stages and long-term storage (Verdon 2014~~, Verdon~~; Verdon et al., 2015~~,~~; McNamara, 2016).

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~~determines 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 (Scholz, 2018). Bearing in mind that ~~CCS~~ GSC onshore reservoirs use to be deep saline aquifers (e.g. Bentham and Kirby, 2005)~~,~~ as the Hontomín ~~is~~ case (Gastine et al., 2017, Le Gallo and de Dios, 2018), ~~and be related to~~which is confined in ~~folding~~ folded and fractured deep geological structures, in which 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. It could occur due to later overlapping geological processes as neoformed mineralization. Also, a low rigidness eludes the slicken fiber formation, and no kinematic data will be marked on the fault plane.~~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~~outcrops ranges between Early Triassic to ~~present-day~~post-Miocene and are mainly located in Cretaceous limestone~~s~~ and dolostone~~s~~ (**Fig. 5, Table 2**). However, ~~N~~no Jurassic outcrops were located, and only seven stations are located on Neogene sediments, ranging between Early Oligocene to Middle-Late Miocene. The ~~short~~ small 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~~ 105 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~~24, ~~26~~25, 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 the recording of conjugate fault systems ~~are~~ is 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~~ 21 were analyzed with the paleostrain technique. Solutions obtained here are robust to establish the paleostrain field in each ~~p~~outcrop as the orientation of the e_y, S_{Hmax} (**Fig~~s~~. 7~~, and 8~~**).

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~~In contrast, 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 ($0º < \beta < 40º$), but also indicates strike-slip faults with normal component for larger dips ($40º < \beta < 90º$). 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).

~~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**).~~

4.2 Late Triassic Outcrop 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~~ constraining this regime with S_{hmin} with NE-SW trending.

4.3 Cretaceous Outcrops Paleostrain

We have divided this result in two groups, (a) outcrops within the 20km circle from HPP and (b) the outcrop the HTM17 (Fig. 5), which is located in the HPP facilities and described in the next section. HTM-14 is the only outcrop from ~~early~~ Early Cretaceous age, showing a compressive tectonic stage with reverse fault solutions, defined by e_y with NE-SW trend~~ing~~ (**Fig. ~~8~~7b and 7c**). Taking into account the extensional stage related to the Main Rifting Stage that took place in Early Cretaceous times (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, 3, 8, 17, 19, 20, 21, 22, 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~~7**). Results are: (1) a compressive stage featured by e_y with NW-SE trend~~ing~~, similar to ~~those~~ the stage described in Tavani (2012), and (2) a normal strain stage with e_y striking both E-W and NE-SW (**Fig. ~~8~~7**, 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, Hontomí~~i~~n Fault, Cantabrian Thrust, Montorio folded band and the ~~anticline~~ Polientes syncline (**Fig. ~~8~~1**).

4.4 Cretaceous Outcrop HTM17 on the Hontomín Pilot Plant

Con formato: Fuente: Cursiva

This outcrop is located on top of the geological reservoir, in a quarry of Upper Cretaceous limestones. The main advantage of this outcrop is the well-development of striation and carbonate microfibers which yields high-quality data. 105 fault-slip data were measured, with the main orientation striking N75°E; N-50ºE; and a conjugate set with N130°E (±10°) trend (Fig. 8). The result of the strain inversion technique shows an extensional field featured by an ey trajectory striking N107°E (±24°) related to an extensional strain field (see the K' diagram in figure 8). Most of the faults are extensional faults ~~(Fig. 9) oriented~~ NE-SW and~~,~~ NW-SE oriented (Fig. 9), in agreement with the extensional RD solution. Reverse faults are oriented NNE-SSW, E-W and WNW-ESE. The advantage of this outcrop is the geographical and stratigraphic position. It is located on top of the HPP facilities in younger sediments than the ~~host rocks for storage~~reservoir rocks. Furthermore, ~~as~~given that the Jurassic ~~host~~reservoir rock and the Cretaceous upper unit are both composed by carbonates, the fault pattern measured here could be a reflex of the fracture network affecting the Jurassic storage rocks in depth (see Figs. 2, 9).

4.~~4~~5 Cenozoic outcrops 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 a local~~n~~ extensional field with e_y with NNE-SSW and N150ºE trend~~ing~~. During the Lower-Middle Miocene~~Miocene~~, HTM15 and HTM30 outcrops exhibit the same e_y ~~striking~~trend~~,~~, but for a compressive tectonic ~~stage~~ regime (**Figs. 7**~~c~~**d**~~ and **8**~~). ~~In addition, during the middle Miocene, an extensional tectonic strain is described and characterized by NNE-SSW and NE-SW trends.~~ HTM1 shows extensional tectonics with ey oriented N50ºE and N130ºE.

Summarizing, the Cenozoic inversion and tectonic compression are detected during the ~~early~~ Early to ~~middle~~ Middle Miocene~~,~~ ~~later to~~and the Oligocene. However,~~, but~~ during the middle Miocene~~,~~ only one extensional stage was interpreted (HTM1, Fig. 7c).

The outcrops located closer to the HPP (HTM 17, 31, 32, **Figs. 5 and 7**)~~,~~ show E-W faults. HTM~~0~~5 is located on the Ubierna Fault, showing a NW-SE trend, whilst HTM~~0~~3 shows ~~strike-slip~~ NE-SW strike-slip. ~~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 parallel to the S_{Hmax} orientation (NNW-SSE and N-S), ~~that~~ could ~~affect~~ induce 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 the Hontomin Fault (**Fig. 5**), a WNW-ESE oriented fault, although the HTM17 station shows that N-S fault planes could play an important role for seepage of fluid into the

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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.~~

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*~~

5.1 Regional active stress tensor in HTM17 fault pattern

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. Namely, the work from Herraiz et al. (2000) calculates three stress tensors within the 20 km of our study area and a Quaternary ~~one~~stress tensor close to the area (c.a. 40 km southward of Hontomín). The age of the first one is Miocene, and defined by σ_1 87°/331°; σ_2 01°/151°; σ_3 00°/061° (dip/dip sense 0º-360º), with an R=0.06 and

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S_{Hmax} trending N151ºE, under an extensional tectonic regime. Two post-Miocene stress tensors are defined by: (1) σ_1 87°/299°; σ_2 00°/209°; σ_3 01°/119° with R = 0.13, S_{Hmax} with N29°E trend under an extensional tectonic regime and (2) σ_1 00°/061°; σ_2 86°/152°; σ_3 03°/331°, with R=0.76, and S_{Hmax} N62°E under strike-slip tectonic regime. Finally, these authors calculated a Quaternary stress tensor defined by: σ_1 85°/183°; σ_2 02°/273°; σ_3 03°/003°; R=0.02 and S_{Hmax} with N101°E trend under an extensional tectonic regime. The regional active stress tensor defined for Pliocene-Quaternary ages is σ_1 88°/197°; σ_2 01°/355°; σ_3 00°/085° for 327 data with R = 0.5 and S_{Hmax} with N-S trend under an extensional tectonic regional regime.

We have applied the regional active stress tensor (Herraiz et al., 2000) for studying the reactivation of previous fault patterns measured in HTM17 (Figs. 8 and 9). To ~~do this~~carry out this study, we assume that the fault plane reactivation depends on σ_1 and σ_3, and the shape of the failure envelope. Therefore, we have used the Mohr-Coulomb failure criteria for preexisting fault planes (Xu et al., 2010; Labuz and Zang, 2012), by using the Mohr Plotter v3.0 code (Allmendinger, 2012). Moreover, to calculate the Mohr-Coulomb circle, it is necessary to know the cohesion and friction parameters ~~of the host rock~~ of the reservoir rock. Bearing in mind that the reservoir rocks are Lower-Jurassic carbonates (dolostone and oolitic limestone, Alcalde et al., 2013, 2014; Ogaya et al., 2013), we have assumed the averaged cohesion for carbonates (limestone and dolostone) in 35º and the coefficient of internal friction of 0.7 (Goodman, 1989). In addition, we have assumed no cohesion with an angle of static friction of 0.7 for preexisting faults.

Figure 10 shows the main results for the Mohr analysis. The reactivated planes under the active-present stress field are red dots, 52 out of the original 1~~1~~05 fault-slip measurements at HTM17. Green and orange dots indicate faults with no tectonic

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strength accumulation under the present-day stress field. Reactivated fault sets are oriented between N to N60ºE and N115º to 180ºE, with N-S and NNE-SSW as main trends (**Fig. 10**, red rose diagram). Under an extensional tectonic field with R = 0.5, N-S are normal faults, whereas NNE-SSW and NNW-SSE trends are strike-slips faults with extensional component. According to the results shown in figure 10, these faults could be reactivated without a pore pressure increase. The inactive fault orientation is constrained between N60ºE and N115ºE, mainly WNW-ESE (**Fig. 10**, green rose diagram). Regarding the uncertainties of these fault orientations, these values can oscillate ±5º, according to the field error measurement (averaged error for measuring structures by a compass).

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Concerning the reliability of the results, some constrains need to be explained. The Mohr-Coulomb failure criterion is an approximation that assumes that the normal stress on the fault plane is not tensile. Furthermore, the increasing of pore pressure in the ~~storage~~reservoir rock reduces the normal stress on the plane of failure and the interval of fault reactivation could be higher. This effect was not considered in the previous analysis since the calculation of the critical pore pressure ~~was out of the focus~~is beyond the purpose of this work. Nevertheless, the MohrPlotter software (Allmendinger, 2012), allows estimating the increase of pore pressure to the critical value under some conditions.

Finally, we have applied the Slip Model and Right Dihedral to the reactivated fault-slip data from HTM17 outcrop (**Fig. 11**), by including the rake estimated from the active regional stress tensor determined by ~~(~~Herraiz et al.~~,~~ (2000). At a glance, faults oriented between N10°E and N10°W act as normal faults (4 out 52, **Figs. 11a, c**), faults between N10°E - N50°E, and N10°W – N50°W act as extensional faults with strike-slip component (31 out 52), and NE-SW and NW-SE vertical faults act as pure strike slips

(8 out 52). The Right Dihedral shows a tectonic regime of strike-slip with extensional component (see De Vicente et al., 1992), with orthorhombic symmetry and S_{Hmax} oriented N10ºW, which is in agreement with the stress-tensor proposed by Herraiz et al. (2000) with σ2 = 01°/355° and σ1 vertical. However, strain analysis in this case shows a strike-slip extensional tectonic regime, instead of the extensional regime derived from the stress field. Despite this, both the Mohr-Coulomb analysis and the Paleostrain analysis (SM and RD), suggest N-S normal faulting, NNE-SSW to NE-SW and NNW-SSE to NW-SE strike-slips as the active fault network affecting the reservoir. De Vicente et al. (1992) pointed out that the SM analysis is more robust applied in fault-slip data classified previously by other techniques. Here, we have used the Mohr Coulomb failure criteria to separate active fault set under the same strain tensor, yielding robustness to the results from SM and RD analysis.

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 base 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 (Landgraf et al., 2018). For example, in Australia heat-flow values as much as 90 mW/m^2 are related with earthquakes sized M > 5 (Holford et al., 2011).

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~~ induced ~~Seismicity~~seismicity

The fluid injection into a deep saline aquifer, which is used as ~~CCS~~GSC, 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).

We have applied a physic model to estimate the total volume injected (room conditions), and then we have applied the McGarr's (2014) approximation. The injection of 10 k tons of CO_2 in Hontomín (Gastine et al., 2017), represents an approximated injected volume of CO_2 of 5.56 x10^6 m^3 (room conditions). We have used the expression Mo(max) (Nm) = G ·ΔV (McGarr 2014, eq. 13), where G is the modulus of rigidity and for the upper limit is 3 x 10^{10} Pa, and ΔV is ~~5.56 x 10^3 m^3 for~~ the total injected volume (in room conditions). The result is Mo(max) equal to 1.67 x 10^{17} Nm (Joules), which corresponds to a maximum seismic moment magnitude M~~o(max)~~ w (max) = ~~6~~5.~~3~~45, ~~of the maximum Richter magnitude~~ by applying the equation Mw = (Log ~~E~~Mo(max) ~~= 11.8 + 1.5·M~~ – 9.05)/1.5 from Hanks and Kanamori (1979); where Log is the logarithm to the base 10~~, E is the seismic released energy in Joules, and M the Richter magnitude~~. McGarr (2014) applied this approach for three cases: (1) wastewater injection, (2) hydraulic fracturing, and (3) geothermal injection. We propose to include this approach for fluid injection related to geological storage of CO_2. We assume that the pore pressure increases from CO_2 injection in a similar way that wastewater does (originally defined by Frohlich, 2012). According to McGarr (2014), the utility of the analysis ~~that~~ we have performed is "to predict in advance of a planned injection whether there will be induced seismicity", and in the case of the ~~Hontomín Pilot Plant~~HPP, ~~by the estimation~~to estimate of the "total injected volume" in a small-scale injection plant. Therefore, ~~T~~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~~4 km and oriented according to the present-day stress field ~~within the influence area~~ (N-S extensional faults and NNE-SSW/NNW-SSE strike slip faults; **Fig. 10**)~~).~~. In the case of HPP, there are faults below the reservoir with this potential earthquake triggering (Alcalde et al., 2014). Also according to McGarr (2014), this value has not to be considered as an absolute physic limit ~~instead~~but as ~~of~~ a qualitative approximation. Alternatively~~On the other hand~~, ~~overpressure increasing the permeability~~increasing by overpressure of the carbonate

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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~~. Besides, these faults are decoupled ~~to~~from the present-day stress tensor. ~~-~~However, N-S faults could act as ~~strike-slip with trans-tensional component~~normal faults and, hence, with 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~~Geological Carbon Storage (~~CCS~~GSC). 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~~ GSC 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 the pore 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 N-S, NNE-SSW and NNW-SSE trends, ~~reverse faults with NW-SE trend and reverse oblique faults oriented E-W,~~ are accumulating present-day tectonic deformation. Analysis of Mohr-Coulomb failure criterion shows a potential reactivation of these fault sets. ~~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~~faults are accumulating tectonic deformation and they could act as normal faults. This means that this fault set ~~are~~ is the preferential ~~fault~~ direction~~s~~ for potential fluid leakage. ~~E-W could act as compressive faults.~~ In addition, intersection with NNE-SSW and NNW-SSE could arrange 3D networks for fluid mobilization and leakage.

(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~~GSC. 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~~an ~~shear~~ extensional tectonic defined by e_y with N-S trend, activating ~~E~~N-~~W~~ S ~~thrust~~ normal faults and right-lateral faults with ~~W~~NNW- and ~~NW~~NNE- trends.

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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FIGURE CAPTIONS

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.

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.

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.

Figure 4. Methodology proposed to obtain the strain field affecting the ~~CCS~~ GSC 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 ey and ex represented are a model for explaining the methodology. Dey and Dex are the direction of the maximum and minimum strain, respectively. Blue box at the center is the CO_2 storage geological underground formation.

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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. Rosd diagram are the fault orientations from the map. 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.

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.

Figure 7. Results of the paleostrain analysis obtained and classified by age. Deym: striking of the averaged of the Dey 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.

Figure 8. Fault data from the outcrop HTM17 located on top of the HPP. See figure 5 for the geographical location. Stereogram plot is lower hemisphere and Schmidt net. ~~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 ey, SHmax trajectories obtained from the outcrops for early Triassic, Early Cretaceous, Late Cretaceous, Early 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.~~

Figure 9. Normal and reverse faults stereograms (lower hemisphere and Schmidt net), and rose diagrams measured in HTM17. Green arrows indicate the orientation of the local paleostrain field. Grey arrows indicate the orientation of the present-day regional stress field (Herraiz et al., 2000).

~~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.~~

Figure 10. Mohr-Coulomb failure analysis for the fault-slip data measured in HTM17 under the present-day stress tensor determined by Herraiz et al. (2000). Red dots are faults reactivated, and green and orange dots are located within the stable zone. Red rose diagram shows the orientation of reactivated faults, between N-S to N60ºE and from N115ºE to N180ºE. Green rose diagram shows the fault orientation for faults non-reactivated under the active tress field within the area. See text for further details.

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Figure 11. a) Stereogram and poles of fault sets (HTM17) reactivated under the present-day stress field suggested by Herraiz et al. (2000). b) Right-Dihedral of the reactivated fault sets. c) K'-strain diagram showing the type of fault for each fault-set.

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TABLE CAPTIONS

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.

Table 2. Summary of the outcrops showing the number of faults, the type of the strain tensor obtained, the Dey, 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.

Con formato: Subíndice

Dear Dave,

Thank you very much for your comments. We agree with your recommendations and consequently, we have included the volume estimation of the total injected brine plus CO_2 in reservoir conditions. Also, a brief explanation about the orange dots obtained in M-C analysis is included in the caption of Figure 10 and finally, we have discussed the role of the slip and dilatation tendency as suggested.

Best regards,

The authors

DETAILED COMMENTS:

I would like to insist on one more change: please calculate the volume of the CO_2 at the reservoir conditions (depth/pressure, temperature) and then re-calculate the maximum predicted moment for comparison to the room conditions value. This is important, as it will surely be less.

New calculation and text:

We have applied a physic model to estimate the total volume injected (room conditions) and in reservoir conditions. Then we have applied the McGarr's (2014) approximation of the maximum expected seismic moment for induced earthquakes. The injection of 10 k tons of CO_2 in Hontomín (Gastine et al., 2017), represents an approximated injected volume of CO_2 of 5.56 x10^6 m^3 (room conditions, pressure of 1 bar and temperature of 20 °C). The P/T conditions at the bottom of the wells have a maximum value close to 190 bar (Ortiz et al., 2015; Kovacs et al., 2015), although oscillating between 125 and 170 bar and with a maximum temperature close to 58 °C. Kovacs et al. (2015) pointed out a pressure gradient 0,023 MPa/m and a thermal vertical gradient of 0.033 °C/m, which would correspond to a pressure of 357 bar and 51 °C at 1,550 m depth. P/T bottom values obtained from the observational wells (HA and HI) by Ortiz et al. (2015) and Kovacs et al. (2015), were 170 bar and 42 °C respectively.

We have used the general law for gases $P_1*V_1/T_1 = P_2*V_2/T_2$. Therefore, the total injected volume in reservoir conditions according to the parameters observed at the bottom of the wells are, P_1= 1.01 bar, T_1= 20 °C, V_1= 5.56 x 10^6 m^3, P_2= 170 bar and T_2= 42 °C. Hence, the total volume of injected CO_2 plus brine is 6.94 x 10^4 m^3.

McGarr (2014) empirically determined the maximum seismic moment related to a volume increasing by underground injection. The expression is Mo(max) (Nm) = G $\cdot\Delta V$ (McGarr 2014, eq. 13), where G is the modulus of rigidity and for the upper limit is 3 x 10^{10} Pa, and ΔV is the total injected volume (we have used the total injected volume in reservoir conditions). The result is Mo(max) equal to 2.1 x 10^{15} Nm, which corresponds to a maximum seismic moment magnitude Mw (max) = 4.2, by applying the equation Mw = (Log Mo(max) – 9.05)/1.5 from Hanks and Kanamori (1979); where Log is the logarithm to the base 10.

The Mohr-Coulomb diagrams in relation to Reviewer 1 comments are good, but you might want to look at slip and dilation tendency (Morris et al., 1996; Ferrill et al., 1999) too, if not for this paper then for the future.

We guess that the complete reference is Morris, Alan, David A. Ferrill and D. Brent Henderson: Slip-tendency analysis and fault reactivation. Geology, 24,275-278. doi: http://doi.org/10.1130/0091-7613(1996)024<0275:STAAFR>2.3.CO;2, 1996.

Yes, we are aware of this type of analysis for fault reactivation and it is totally complementary with our work. In fact, applying this analysis is similar because both analyses are based on the same concepts: stress tensor (R and K) and the fault orientation. Moreover, if you see the original paper of Morris et al. (1996), Fig. 4A shows σ_2 with N-S trend and σ_3 with E-W trend, under a strike-slip stress tensor. In this context, the most likelihood fault orientation to slip reactivation is N-S with dip greater than 59°. These values are similar to our results in Hontomin, with the same stress tensor and fault orientation than Morris et al. (1996), but in the Basque Cantabria basin instead of Yucca Mountains. The most interesting thing is that results are similar in both cases. Anyway, we can perform this kind of analysis combined with our analysis but as you say, for future works. Even so, we have mentioned this type of analysis in Discussion section of fault reactivation. Thank you for the suggestion.

Included text:

We propose as a complementary and future work, a combined analysis between the fault population analysis and the slip-tendency analysis (Morris et al. 1996), which could improve and discriminate those fault sets most likely to be reactivated under an active stress field. Although both analyses (Fault Population and slip-tendency) are based on the stress tensor and the orientation of fault traces, the slip-tendency also includes rock strength values obtained from the "in situ" tests.

Also, what are the yellow data on the M-C plot? They do not have a corresponding rose plot...

The yellow data in the M-C diagrams are referred to those planes close to be reactivated, and potentially reactivated by increasing the pore pressure.

We have included this sentence in the caption of Figure 9.

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

Raúl Pérez-López[1], José F. Mediato[1], Miguel A. Rodríguez-Pascua[1], Jorge L. Giner-Robles[2], Adrià Ramos[1], Silvia Martín-Velázquez[3], Roberto Martínez-Orío[1], Paula Fernández-Canteli[1]

1. IGME – Instituto Geológico y Minero de España – Geological Survey of Spain. C/Ríos Rosas 23, Madrid 28003 – SPAIN. Email: r.perez@igme.es, jf.mediato@igme.es, ma.rodriguez@igme.es, a.ramos@igme.es, ro.martinez@igme.es, paula.canteli@igme.es
2. Departamento de Geología y Geoquímica. Facultad de Ciencias. Universidad Autónoma de Madrid. Campus Cantoblanco, Madrid. SPAIN. Email: jorge.giner@uam.es
3. Universidad Rey Juan Carlos. Email: silvia.martin@urjc.es

Abstract

One of the concerns of underground CO_2 onshore storage is the triggering of Induced Seismicity and fault reactivation by pore pressure increasing. 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 from Triassic to Miocene. 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 ~~about~~ of CO_2 leakage and seepage. We have applied this methodology to Hontomín

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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 kinematics fault analysis. The results indicate a strike-slip tectonic regime with the maximum horizontal shortening with N160°E and N50ºE trend for local regime, which activates NE-SW strike-slip faults. A regional extensional tectonic field was also recognized with N-S trend, which activates N-S extensional faults, and NNE-SSW and NNW-SSE strike-slip faults, measured in the Cretaceous limestone on top of the Hotomín facilities. Monitoring these faults within the reservoir is suggested in addition ~~with~~ 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. The Geological Carbon Storage (GSC) 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 GSC (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 earthquakes triggering, with the consequence of leakage and seepage, and (2) the long-term reservoir behavior, understanding as long-term from centennial to millennial time-span. Therefore, what is the long-term behavior of GSC? What do we need to monitor for a safe GSC 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 GSC 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 large as M 1.7, detected in swarms about 9,500 microearthquakes, are related to GSC operations. Additionally, Foulger et al. (2018) pointed out that GSC can trigger earthquakes with magnitudes lesser than M 2, namely the cases described in their work are as great as M 1.8, with the epicenter location 2 km around the facilities. McNamara (2016) described a comprehensive method and protocol for monitoring GSC 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 of 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 GSC 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) analysis between 20 away from the subsurface reservoir deep geometry, under the area of influence of induced seismicity for fluid injection. The knowledge of the strain field at local scale allows classifying the type of faulting and their role for leakage processes, whilst the regional scale explores the tectonic active faults that 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 directly classification of all the faults involved into the geomechanical model and the prediction of the failure parameters. Besides, a Mohr-Coulomb failure analysis was performed to the fault pattern recognized in the Cretaceous outcrop located on top of the pilot plant.

The tectonic characterization of the GSC 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 analysis to manage underground storage operations. We present how the Structural Analysis of fault/slip data can improve the knowledge of the tectonic large-scale fault network for the potential seismic reactivation during fluid injection and time-depend scale for fluid stays.

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 (Dallmeyer and Martínez-García, 1990; Calvet et al., 2004), 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; Le Pichon and Sibuet, 1971; Lepvrier and Martínez-García, 1990; García-Mondéjar et al., 1996; 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 Mesozoic extensional faults and the development of an E-W orogenic belt (Cantabrian domain to the west and Pyrenean domain to the east) formed along the northern Iberian plate margin (Muñoz, 1992; Gómez et al., 2002; Vergés et al., 2002).

The Hontomín facilities are located within the Basque-Cantabrian Basin (**Fig. 1b**). The geological reservoir 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 is defined as a forced fold related dome structure (Tavani et al., 2013; **Fig. 2**), 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 the Alpine Orogeny affecting the Pyrenees, the right-lateral transpressive inversion of the basement faults was activated, along with the reactivation of transverse extensional faults (**Fig. 2**; Tavani et al., 2013; Alcalde et al., 2014).

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 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 acts as 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 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 tectonic 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 tectonic regime as uniaxial extension to strike-slip with NW-SE S_{Hmax} trend.

Regional data about the tectonic field 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}. These works explain the tectonic framework for regional scale. Nevertheless, local tectonics could determine the low permeability and the potential induced seismicity within the 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*). The 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 GSC managing in the frame of geological risk, is based on the strain tensor calculation, as part of the objectives proposed in the European project "ENabling Onshore CO2 Storage in Europe" (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 GSC 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 GSC 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".

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 (dip/ dip direction and rake), in several outcrops in the surroundings of the onshore reservoir. 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. Finally, we have studied the fault plane reactivation by using the Mohr-Coulomb failure criterion (Pan et al., 2016), from the fault pattern obtained in the Cretaceous limestone outcrop located on top of the HPP facilities.

3.1 *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:

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

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

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 defines 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 dip values lower than 45º, 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 e_y SM results.

Resolving the equations of Anderson for different values (Anderson, 1951), we can classify the tectonic regime that activates one fault from the measurement of the fault dip, sense of dip (0º-360º) and pitch of the slickenside, assuming that one of the principal axes (e_x, e_y or e_z) is vertical (Angelier, 1984). We can classify 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 ($p < 25^{o}$), and dips close to vertical planes ($\beta > 75^{o}$). High pitch values ($p > 60^{o}$) 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 (Kaverina et al., 1996). 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 earthquake magnitudes 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.

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.

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 GSC reservoir, which will allow the long-term monitoring of the geological and seismic behavior (**Fig. 4**). The objective is to obtain enough structural data and spatially homogeneous of faults (**Figs. 4, 5**) for reconstructing the stress/strain tensor. 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.

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 GSC reservoir is mainly related to the operations during the injection/depletion stages and long-term storage (Verdon 2014; Verdon et al., 2015; McNamara, 2016).

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 determines 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 (Scholz, 2018). Bearing in mind that GSC onshore reservoirs use to be deep saline aquifers (e.g. Bentham and Kirby, 2005) as the Hontomín case (Gastine et al., 2017, Le Gallo and de Dios, 2018), which is confined in folded and fractured deep geological structures, in which 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. It could occur due to later overlapping geological processes as neoformed mineralization. Also, a low rigidness eludes the slicken fiber formation, and no kinematic data will be marked on the fault plane.. 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 outcrops ranges between Early Triassic to post-Miocene and are mainly located in Cretaceous limestone and dolostone (**Fig. 5, Table 2**). However, no Jurassic outcrops were located, and only seven stations are located on Neogene sediments, ranging between Early Oligocene to Middle-Late Miocene. The small 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 105 faults on Cretaceous limestone. Conjugate fault systems can be recognized in most of the stations (HTM1, 3, 5, 7, 10, 14, 16, 21, 23, 24, 25, 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 the recording of conjugate fault systems is 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, 21 were analyzed with the paleostrain technique. Solutions obtained here are robust to establish the paleostrain field in each outcrop as the orientation of the e_y, S_{Hmax} (**Fig. 7,**).

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.

In contrast, 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 HTM2 the K'-diagram indicates strike-slip faults with reverse component for low dips (0º < β < 40º), but also indicates strike-slip faults with normal component for larger dips (40º < β < 90º). 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), Tavani et al. (2011) and Alcalde et al. (2014).

4.2 Late Triassic Outcrop 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**). This is in agreement with the uniaxial extension described in Tavani (2012), constraining this regime with S_{hmin} with NE-SW trending.

4.3 Cretaceous Outcrops Paleostrain

We have divided this result in two groups, (a) outcrops within the 20km circle from HPP and (b) the outcrop the HTM17 (**Fig. 5**), which is located in the HPP facilities and described in the next section. HTM14 is the only outcrop from Early Cretaceous age, showing a compressive tectonic stage with reverse fault solutions, defined by e_y with NE-SW trend (**Fig. 7b and 7c**). Taking into account the extensional stage related to the Main Rifting Stage that took place in Early Cretaceous times (i.e. Carola, 2004; Tavani, 2012; Tugend et al., 2014), we interpreted these results as a modern strain field, probably related to the Cenozoic Inversion stage.

Outcrops HTM 2, 3, 8, 17, 19, 20, 21, 22, 23, 25, 26, 29, 31 and 32 are from the upper Cretaceous carbonates (**Fig. 7**). Results are: (1) a compressive strain stage featured by e_y with NW-SE trend, similar to the stage described in Tavani (2012), and (2) a normal strain stage with e_y striking both E-W and NE-SW (**Fig. 7**, HTM 20, 21, 31 and 32). Finally, a (3) shear stage (activated strike-slip faults) and (4) a shear with 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, Hontomín Fault, Cantabrian Thrust, Montorio folded band and the Polientes syncline (**Fig. 1**).

4.4 Cretaceous Outcrop HTM17 on the Hontomín Pilot Plant

This outcrop is located on top of the geological reservoir, in a quarry of Upper Cretaceous limestones. The main advantage of this outcrop is the well-development of striation and carbonate microfibers which yields high-quality data. 105 fault-slip data were measured, with the main orientation striking N75°E; N-50ºE; and a conjugate set with N130°E (±10°) trend (**Fig. 8**). The result of the strain inversion technique shows an extensional field featured by an ey trajectory striking N107°E (±24°) related to an extensional strain field (see the K’ diagram in **figure 8**). Most of the faults are extensional faults NE-SW and NW-SE oriented (**Fig. 9**), in agreement with the extensional RD solution. Reverse faults are oriented NNE-SSW, E-W and WNW-ESE. The advantage of this outcrop is the geographical and stratigraphic position. It is located on top of the HPP facilities in younger sediments than the reservoir rocks. Furthermore, given that the Jurassic reservoir rock and the Cretaceous upper unit are both composed by carbonates, the fault pattern measured here could be a reflex of the fracture network affecting the Jurassic storage rocks in depth (see **Figs. 2, 9**).

4.5 Cenozoic outcrops 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**) shows a local extensional field with e_y with NNE-SSW and N150ºE trend. During the Lower-Middle Miocene, HTM15 and HTM30 outcrops exhibit the same e_y trend, but for a compressive tectonic regime (**Figs. 7d**). HTM1 shows extensional tectonics with ey oriented N50ºE and N130ºE. Summarizing, the Cenozoic inversion and tectonic compression are detected during the Early to Middle Miocene and the Oligocene. However, during the middle Miocene only one extensional stage was interpreted (HTM1, **Fig. 7c**).

The outcrops located closer to the HPP (HTM 17, 31, 32, **Figs. 5 and 7**) show E-W faults. HTM5 is located on the Ubierna Fault, showing a NW-SE trend, whilst HTM3 shows NE-SW strike-slip.

Strain analysis suggests that the planes parallel to the S_{Hmax} orientation (NNW-SSE and N-S), could induce the leakage into the reservoir (**Fig. 7**). Moreover, N50ºE S_{Hmax} orientation could also affect the reservoir. HPP facilities are close to the Hontomin Fault (**Fig. 5**), a WNW-ESE oriented fault, although the HTM17 station shows that N-S fault planes could play an important role for seepage of fluid into the reservoir.

5. DISCUSSION

5.1 Regional active stress tensor in HTM17 fault pattern

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. Namely, the work from Herraiz et al. (2000) calculates three stress tensors within the 20 km of our study area and a Quaternary stress tensor close to the area (c.a. 40 km southward of Hontomín). The age of the first one is Miocene, and defined by σ_1 87°/331°; σ_2 01°/151°; σ_3 00°/061° (dip/dip sense 0º-360º), with an R=0.06 and S_{Hmax} trending N151ºE, under an extensional tectonic regime. Two post-Miocene stress tensors are defined by: (1) σ_1 87°/299°; σ_2 00°/209°; σ_3 01°/119° with R = 0.13, S_{Hmax} with N29°E trend under an extensional tectonic regime and (2) σ_1 00°/061°; σ_2 86°/152°; σ_3 03°/331°, with R=0.76, and S_{Hmax} N62°E under strike-slip tectonic regime. Finally, these authors calculated a Quaternary stress tensor defined by: σ_1 85°/183°; σ_2 02°/273°; σ_3 03°/003°; R=0.02 and S_{Hmax} with N101°E trend under an extensional tectonic regime. The regional active stress tensor defined for Pliocene-Quaternary ages is σ_1 88°/197°; σ_2 01°/355°; σ_3 00°/085° for 327 data with R = 0.5 and S_{Hmax} with N-S trend under an extensional tectonic regional regime.

We have applied the regional active stress tensor (Herraiz et al., 2000) for studying the reactivation of previous fault patterns measured in HTM17 (**Figs. 8** and **9**). To carry out this study, we assume that the fault plane reactivation depends on σ_1 and σ_3, and the shape of the failure envelope. Therefore, we have used the Mohr-Coulomb failure criteria for preexisting fault planes (Xu et al., 2010; Labuz and Zang, 2012), by using the Mohr Plotter v3.0 code (Allmendinger, 2012). Moreover, to calculate the Mohr-Coulomb circle, it is necessary to know the cohesion and friction parameters of the reservoir rock. Bearing in mind that the reservoir rocks are Lower-Jurassic carbonates (dolostone and oolitic limestone, Alcalde et al., 2013, 2014; Ogaya et al., 2013), we have assumed the averaged cohesion for carbonates (limestone and dolostone) in 35º and the coefficient of internal friction of 0.7 (Goodman, 1989). In addition, we have assumed no cohesion with an angle of static friction of 0.7 for preexisting faults.

Figure 10 shows the main results for the Mohr analysis. The reactivated planes under the active-present stress field are red dots, 52 out of the original 105 fault-slip measurements at HTM17. Green and orange dots indicate faults with no tectonic strength accumulation under the present-day stress field. Reactivated fault sets are oriented between N to N60ºE and N115º to 180ºE, with N-S and NNE-SSW as main trends (**Fig. 10**, red rose diagram). Under an extensional tectonic field with R = 0.5, N-S are normal faults, whereas NNE-SSW and NNW-SSE trends are strike-slips faults with extensional component. According to the results shown in figure 10, these faults could be reactivated without a pore pressure increase. The inactive fault orientation is constrained between N60ºE and N115ºE, mainly WNW-ESE (**Fig. 10**, green rose diagram). Regarding the uncertainties of these fault orientations, these values can oscillate ±5º, according to the field error measurement (averaged error for measuring structures by a compass).

Concerning the reliability of the results, some constrains need to be explained. The Mohr-Coulomb failure criterion is an approximation that assumes that the normal stress on the fault plane is not tensile. Furthermore, the increasing of pore pressure in the reservoir rock reduces the normal stress on the plane of failure and the interval of fault reactivation could be higher. This effect was not considered in the previous analysis since the calculation of the critical pore pressure is beyond the purpose of this work.

Nevertheless, the MohrPlotter software (Allmendinger, 2012), allows estimating the increase of pore pressure to the critical value under some conditions.

Finally, we have applied the Slip Model and Right Dihedral to the reactivated fault-slip data from HTM17 outcrop (**Fig. 11**), by including the rake estimated from the active regional stress tensor determined by Herraiz et al. (2000). At a glance, faults oriented between N10°E and N10°W act as normal faults (4 out 52, **Figs. 11a, c**), faults between N10°E - N50°E, and N10°W – N50°W act as extensional faults with strike-slip component (31 out 52), and NE-SW and NW-SE vertical faults act as pure strike slips (8 out 52). The Right Dihedral shows a tectonic regime of strike-slip with extensional component (see De Vicente et al., 1992), with orthorhombic symmetry and S_{Hmax} oriented N10ºW, which is in agreement with the stress-tensor proposed by Herraiz et al. (2000) with $\sigma 2$ = 01°/355° and $\sigma 1$ vertical. However, strain analysis in this case shows a strike-slip extensional tectonic regime, instead of the extensional regime derived from the stress field. Despite this, both the Mohr-Coulomb analysis and the Paleostrain analysis (SM and RD), suggest N-S normal faulting, NNE-SSW to NE-SW and NNW-SSE to NW-SE strike-slips as the active fault network affecting the reservoir. De Vicente et al. (1992) pointed out that the SM analysis is more robust applied in fault-slip data classified previously by other techniques. Here, we have used the Mohr Coulomb failure criteria to separate active fault set under the same strain tensor, yielding robustness to the results from SM and RD analysis.

We propose as a complementary and future work, a combined analysis between the fault population analysis and the slip-tendency analysis (Morris et al. 1996), which could improve and discriminate those fault sets most likely to be reactivated under an active stress field. Although both analyses (Fault Population and slip-tendency) are based on the stress tensor and the orientation of fault traces, the slip-tendency also includes rock strength values obtained from the "in situ" tests.

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 base 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 (Landgraf et al., 2018). For example, in Australia heat-flow values as much as 90 mW/m^2 are related with earthquakes sized M > 5 (Holford et al., 2011).

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.

5.3 Local tectonic field and induced seismicity

The fluid injection into a deep saline aquifer, which is used as GSC, 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).

We have applied a physic model to estimate the total volume injected (room conditions) and in reservoir conditions.~~, and t~~Then we have applied the McGarr's (2014) approximation of the maximum expected seismic moment for induced earthquakes. The injection of 10 k~~-~~tons of CO_2 in Hontomín (Gastine et al., 2017), represents an approximated injected volume of CO_2 of 5.56 x10^6 m^3 (room conditions, pressure of 1 bar and temperature of 20 °C).~~-~~. The P/T conditions at the bottom of the wells have a maximum value close to 190 bar (Ortiz et al., 2015; Kovacs et al., 2015), although oscillating between 125 and 170 bar and with a maximum temperature close to 58 °C. Kovacs et al. (2015) pointed out a pressure gradient 0.023 MPa/m and a thermal vertical gradient of 0.033 °C/m, which would correspond to a pressure of 357 bar and 51 °C at 1,550 m depth. P/T bottom values obtained from the observational wells (HA and HI) by Ortiz et al. (2015) and Kovacs et al. (2015), were 170 bar and a temperature of 42 °C respectively.

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We have used the general law for gases $P_1*V_1/T_1 = P_2*V_2/T_2$. Therefore, the total injected volume in reservoir conditions according to the parameters observed at the bottom of the wells are, P_1= 1.01 bar, T_1= 20 °C, V_1= 5.56 x 10^6 m^3, P_2= 170 bar and T_2= 42 °C. Hence, the total volume of injected CO_2 plus brine is 6.94 x 10^4 m^3.

McGarr (2014) empirically determined the maximum seismic moment related to a volume increasing by underground injection. The expression is Mo(max) (Nm) = $G \cdot \Delta V$

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(McGarr 2014, eq. 13), where G is the modulus of rigidity and for the upper limit is 3 x 10^{10} Pa, and ΔV is the total injected volume (we have used the total injected volume in reservoir conditions). The result is Mo(max) equal to 2.1 x 10^{15} Nm, which corresponds to a maximum seismic moment magnitude Mw (max) = 4.2, by applying the equation Mw = (Log Mo(max) – 9.05)/1.5 from Hanks and Kanamori (1979); where Log is the logarithm to the base 10.

~~We have used the expression Mo(max) (Nm) = G ·ΔV (McGarr 2014, eq. 13), where G is the modulus of rigidity and for the upper limit is 3 x 10^{10} Pa, and ΔV is the total injected volume (in room conditions). The result is Mo(max) equal to 1.67 x 10^{17} Nm (Joules), which corresponds to a maximum seismic moment magnitude Mw (max) = 5.45, by applying the equation Mw = (Log Mo(max) – 9.05)/1.5 from Hanks and Kanamori (1979); where Log is the logarithm to the base 10.~~

Con formato: Resaltar

McGarr (2014) applied this approach for three cases: (1) wastewater injection, (2) hydraulic fracturing, and (3) geothermal injection. We propose to include this approach for fluid injection related to geological storage of CO_2. We assume that the pore pressure increases from CO_2 injection in a similar way that wastewater does (originally defined by Frohlich, 2012). According to McGarr (2014), the utility of the analysis we have performed is "to predict in advance of a planned injection whether there will be induced seismicity", and in the case of the HPP, to estimate of the "total injected volume" in a small-scale injection plant.

Therefore, the earthquake magnitude to this fluid-injected volume according to the McGarr (2014) and Verdon et al. (2014) could be M > ~~5~~ 4 if there are faults with a minimum size of 4 km and oriented according to the present-day stress field (N-S extensional faults and NNE-SSW/NNW-SSE strike slip faults; **Fig. 10**). In the case of HPP, there are faults below the reservoir with this potential earthquake triggering

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(Alcalde et al., 2014). Also according to McGarr (2014), this value has not to be considered as an absolute physic limit but as a qualitative approximation. Alternatively, increasing by overpressure 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. Besides, these faults are decoupled from the present-day stress tensor. However, N-S faults could act as normal faults and, hence, with higher permeability. 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 active tectonic ~~evolution of the~~ strain field, applied in the ongoing seismic monitoring for Geological Carbon Storage (GSC). 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~~ the 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 GSC 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 the pore overpressure. 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 N-S, NNE-SSW and NNW-SSE trends, are accumulating present-day tectonic deformation. Analysis of Mohr-Coulomb failure criterion shows a potential reactivation of these fault sets.

(4) N-S faults are accumulating tectonic deformation and they could act as normal faults. This means that this fault set is the preferential direction for potential fluid leakage. In addition, intersection with NNE-SSW and NNW-SSE could arrange 3D networks for fluid mobilization and leakage.

(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 GSC. 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), and the total injected fluid could trigger induced earthquakes greater than M 4. ~~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 an extensional tectonic defined by e_y with N-S trend, activating N-S normal faults and right-lateral faults with NNW- and NNE- trends.

Finally, we state that the determination of the active tectonic strain field, the application of the slip-tendency analysis, 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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Código de campo cambiado

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FIGURE CAPTIONS

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.

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.

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.

Figure 4. Methodology proposed to obtain the strain field affecting the GSC 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 ey and ex represented are a model for explaining the methodology. Dey and Dex are the direction of the maximum and minimum strain, respectively. Blue box at the center is the CO_2 storage geological underground formation.

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. Rosd diagram are the fault orientations from the map. 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.

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.

Figure 7. Results of the paleostrain analysis obtained and classified by age. Deym: striking of the averaged of the Dey 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.

Figure 8. Fault data from the outcrop HTM17 located on top of the HPP. See figure 5 for the geographical location. Stereogram plot is lower hemisphere and Schmidt net.

Figure 9. Normal and reverse faults stereograms (lower hemisphere and Schmidt net), and rose diagrams measured in HTM17. Green arrows indicate the orientation of the local paleostrain field. Grey arrows indicate the orientation of the present-day regional stress field (Herraiz et al., 2000).

Figure 10. Mohr-Coulomb failure analysis for the fault-slip data measured in HTM17 under the present-day stress tensor determined by Herraiz et al. (2000). Red dots are faults reactivated, and green and orange dots are located within the stable zone. Red rose diagram shows the orientation of reactivated faults, between N-S to N60ºE and from N115ºE to N180ºE. Green rose diagram shows the fault orientation for faults non-reactivated under the active tress field within the area. See text for further details. The yellow data in the M-C diagrams are referred to those planes close to be reactivated, and potentially reactivated by increasing the pore pressure.

Figure 11. a) Stereogram and poles of fault sets (HTM17) reactivated under the present-day stress field suggested by Herraiz et al. (2000). b) Right-Dihedral of the reactivated fault sets. c) K'-strain diagram showing the type of fault for each fault-set.

TABLE CAPTIONS

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.

Table 2. Summary of the outcrops showing the number of faults, the type of the strain tensor obtained, the Dey, S_{Hmax} striking and the age of the affected geological materials. N-C is normal component for strike-slip movement.