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Full Length Research Paper

A preliminary selection of regions in Mexico with potential for geological carbon storage

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Using a compilation of information about Mexican surficial geology and recent tectonic activity, zones for possible geological carbon storage were defined. There were seven zones defined on the basis of volcanic, geologic, lithologic, seismic and tectonic features. Most importantly at this stage, zones of exclusion were defined in which geologic storage is not recommended. These zones will aid in further exploration of the geological carbon storage possibilities in Mexico.

Key words: Carbon dioxide, geological carbon storage, seismic, volcanic hazards, Mexico.

INTRODUCTION

With rising concerns over world carbon dioxide emissions, it is prudent to explore methods by which emissions can be reduced. Mexico is the world's twelfth largest emitter of carbon dioxide, having emitted 119 million metric tons in 2006, about 1.4% of world greenhouse gas emissions that year (Boden et al., 2009). The main goal of CFE (Comisión Federal de Electricidad) governmental agency is to provide electricity to the increasing population of Mexico, which requires the construction of more power plants throughout the country. However because of environmental policies, international agreements, social responsibility and a corporate commitment to the environment, CFE has begun to explore the possibility of geologic carbon storage in Mexico. Geologic carbon sequestration allows for permanent storage of carbon dioxide in geological formations as a method of carbon emissions reduction.

Several such facilities are operational throughout the world (Gale et al., 2001; Metz et al., 2005; Jensen et al., 2009; Eccles et al., 2009) and some others are in the planning and development stages (USDOE, 2008; Schilling et al., 2009; Grataloup et al., 2009).

According to Bachu et al. (2007), studies of CO_2 storage capacity in geological media depend on the scale and resolution of the assessment. The scale categories comprise five sizes of geographical areas: country, basin, regional, local and site-scale. In contrast, three levels of detail and resolution were proposed and vary from low and medium to high level data. In the country-scale assessment is usually considered the identification of areas encompassing sedimentary basins and types of storage capacities available. The data requirements and resolution are minimal, usually found in the public domain. This study depicts the country-level assessment in preparation for the basin-scale assessment, which is now being pursued by the authors at CFE. This paper represents a preliminary study on the geological carbon storage possibilities in Mexico by studying the seismic, volcanic and tectonic hazards in combination with the surface geology and lithology. The country was split up into seven zones based on these characteristics, excluding some areas from further study and categorizing those with more potential for future more in depth and

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Abbreviations: CFE, Comisión Federal de Electricidad, CIIEMAD-IPN, Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo-Instituto Politécnico Nacional subsurface studies.

MATERIALS AND METHODS

Methods

Information and maps on the geology, tectonics, lithology and seismic and volcanic hazards were gathered from a variety of sources, especially from governmental and research institutions that have large databases of information such as CENAPRED (Centro Nacional de Prevención de Desastres, 2009) and SSN (Servicio Sismológico Nacional, 2009). This information was compiled into a database which contains more than 500 articles and maps. The size of the database makes it impossible to cite all the sources, but they can be obtained upon request to the authors. The information was studied and screened in order to be placed on a series of thematic maps of Mexico. Once these maps were obtained they were compared and combined into a final map of zones of geological carbon storage potential using geographic information software (ESRI-Arc GIS).

The criteria used to analyze the information were selected according to the hazardous potential they represent in Mexico. The tectonic scenario is particularly important in terms of the presence of a convergent margin and a volcanic arc that are currently actives. Compressive and extensional tectonic stress regimes are represented mainly by the interplay of the Cocos, Pacific and North American tectonic plates and several magmatic processes. These phenomena also lead the formation of surface faulting. An active fault is defined as a fault which has had seismic activity or displaced earth materials during the last 10,000 or so years before present. Examples of the strong seismic activity are the September 1985 coastal pacific Michoacán earthquake, magnitude 8.1 (Priestley and Masters, 1986) and the June 15, 1999, earthquake magnitude 7.0 occurred in central Mexico (Yamamoto et al., 2002), among many others. The emplacement and recorded activity of the largest active volcanoes of Mexico, such as the Popocatepetl, Citlaltepetl and Colima are the proof of recent and repetitive volcanic eruptions during the last thousand of years (Macias, 2005).

Beside the above mentioned risky processes, the type and distribution of geological formations cropping out, the geothermal resources, the location of oil and gas productive provinces, coal basins and enhanced oil recovery zones (Santiago et al., 1984; Ortega et al., 1992; CFE-GEIC, 2000 - 2009; CFE-GEOTERMIA, 2009) received extensive consideration during this study, since onshore and offshore sedimentary basins, oil and gas or brine reservoirs and unmineable coal beds are potential candidates for CO_2 storage.

This type of data accumulation and information allows for continued updates and modifications with the addition of more in-depth data, therefore providing a tool that will continue to be useful throughout the exploration stages of this project.

Tectonics and seismic and volcanic hazards

Mexico is characterized by several geologic provinces (López-Ramos, 1979; INEGI, 1982; Campa and Coney, 1983; Ortega et al., 1992; Lugo and Córdova, 1995; SGM, 2007) (Figure 1a) which are related to the evolution of the most important stratigraphic and tectonic features. The current tectonics of Mexico is dominated by the Mexican subduction zone located along the southwest Pacific Coast, the rifting system in the northwest beneath the Gulf of California and the Motagua Polochic fault system in the South-South East part of the country (Figure 1b) (Elders, 1972; Burkart,1983; Burkart and Self, 1985; Wallace, 1984; Luhr, 1985; Allan, 1986; Meneses, 1986; Londsdale, 1989; Pardo and Suarez, 1995; Hirabayashi et al., 1996; DeMetz and Wilson, 1997). These tectonic and large scale structural geology features, when active, are potential hazards for a geological storage facility and sources for many of the seismic and volcanic hazards. Volcanoes are mostly concentrated inland of the Middle America Trench, as shown by the locations of active faults, volcanoes, calderas and geothermic fields (Figure 1b) (Urbina and Camacho, 1913, Demant, 1978; Yáñez and García, 1982, Pearthree, 1986; Martínez and Nieto, 1990; Johnson and Harrison, 1990; Garduño and Gutiérrez 1992; Righter, 1995; Suter, 1995; Nieto et al., 1997; González, 1999; Aguirre, 2001; Macías, 2005; Gracía-Palomo et al., 2006; Andreani et al., 2008).

Although, the seismicity records of the last 100 years were considered (Singh et al., 1984; CENAPRED, 2001; SSN, 2009), only the location and magnitude (quantified on the Richter scale) of seismic events with a magnitude greater than 5, that have occurred in Mexico since 1998, are shown on Figure 1b. Note that the earthquakes are mostly concentrated along the plate boundaries. The recurrence time of the largest earthquakes in México has been estimated between 30 to 50 years (Singh et al., 1981; Santoyo et al., 2005; Suarez and Albini, 2009). This leaves areas of the country with low seismic hazards as possibilities for geologic carbon storage.

Additionally Figure 1c shows the location of hydrothermal activity, which is related to extensive plutonic and volcanic activity in the whole country. Actually, the data shown is the enthalpy distribution which can be defined more or less proportional to temperature. In these hydrothermal sites, the heat of the fluids is expressed roughly as thermal energy. This means, that the fluids act as the carrier transporting heat from the deep hot rocks to the surface reflecting the thermal conditions of the upper crust (CFE-Geotermia, 2009). Otherwise, this information is used as well as reference for the geothermal resources development in Mexico (Birkle, 2007; Gutiérrez-Negrín, 2009).

Lithology and geology

The lithology and geology was explored only at the surface level at this stage and a simplified geologic map of the country is shown in Figure 1d. In general the country has a backbone of felsic igneous rocks in the Sierra Madre Occidental mountain chain (Delgado and Martin, 1993; Aranda, 2000; Ferrari, 2000), as well as in the Baja California Peninsula (Gastil et al., 1975; Martín, 2000; Sedlock, 2003). The area inland of the Middle American Trench is composed mainly by mafic igneous rocks that form the Transmexican Volcanic Belt (Demant, 1978; Robin, 1982; Nixon, 1982; Mooser, 1992; Ferrari, 2000; Gómez et al., 2005) and metamorphic, igneous and sedimentary rocks shaping up the Sierra Madre del Sur (Morán et al., 2005). The other portions of the country especially the Gulf Coast and the Gulf of Mexico region is composed of sedimentary terrigenous, calcareous and evaporitic rock sequences as well as the Sierra Madre Oriental Folded Belt and Sierra de Chiapas (Burckhardt, 1930; Buffler and Sawyer, 1985; Michaud, 1987; Pindell, 1993; Padilla, 2007). The sedimentary rocks hold possibilities for geological carbon storage and should be explored further. At this point in time, we consider igneous rocks to be less favorable for carbon storage, thought basalts could be used for storage by mineralization as the technology develops in the future (Prasad et al., 2009). The areas of less-favorable igneous rocks also tend to overlap with seismic and volcanic hazards.

The location and distribution of petroleum productive provinces, coal beds and enhanced oil recovery zones agreed with the allocation of the main sedimentary basins all over the country (Figure 2) (Santiago et al., 1984; USGS, 1997; CFE-GEIC, 2000 - 2009). Various limitations imposed by technical, economic and protective regulatory restrictions indicate that the division of Mexico into regions requires no major changes in the energy infrastructure and the coincidence of CO_2 emission sources to storage sites. It is evident that the Northern, Eastern and Southeastern regions of Mexico are the most promising areas for CO_2 geological storage.

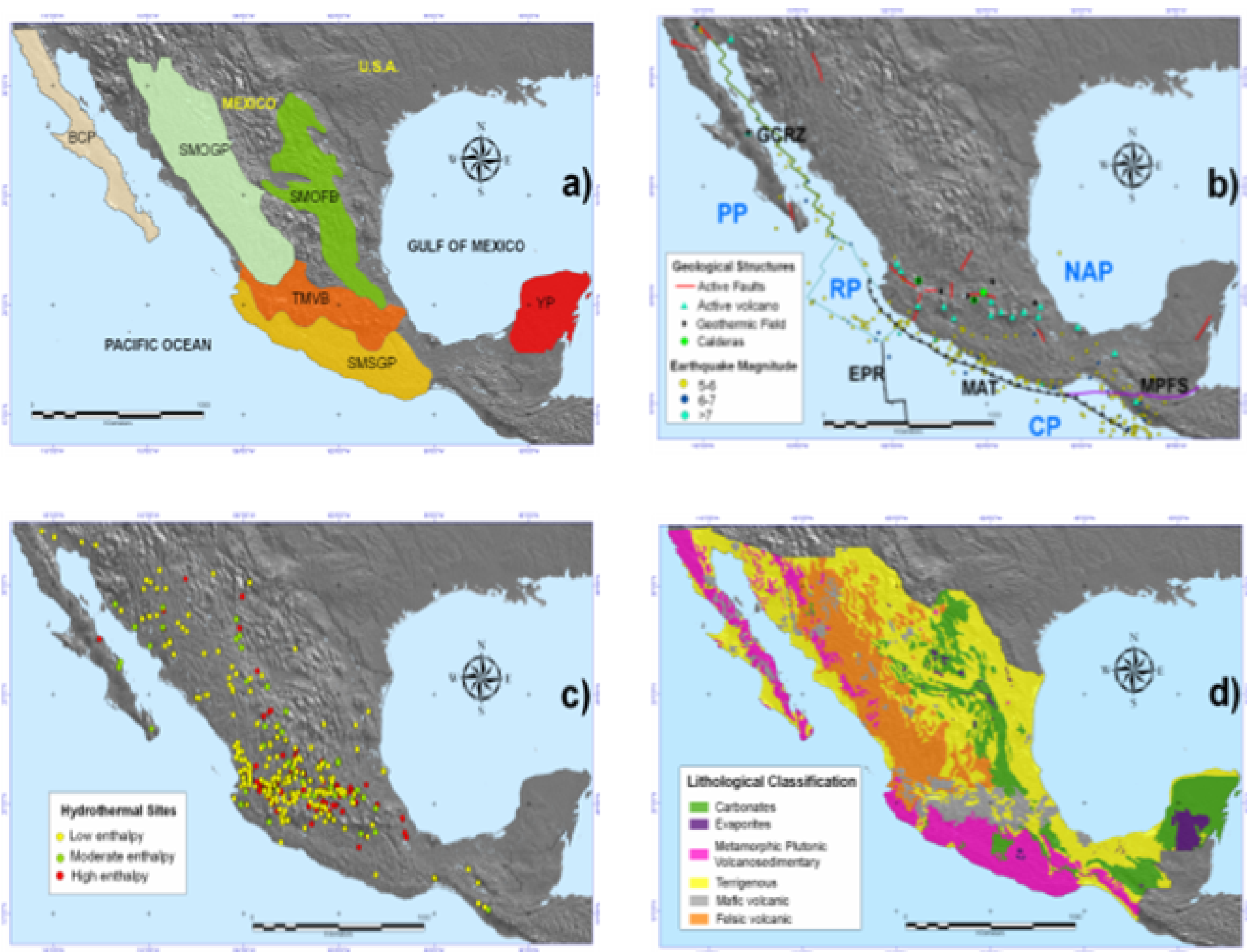

Figure 1. Thematic maps of Mexico.
(a) Map of geologic provinces.
BCP, Baja California Peninsula; **SMOGP,** Sierra Madre Occidental Geologic Province; **SMOFB,** Sierra Madre Oriental Folded Belt; **TMVB,** TransMexican Volcanic Belt; **SMSGP,** Sierra Madre del Sur Geologic Province; **YP,** Yucatan Peninsula.
(b) Map showing the location of the seismotectonic structures and volcanic features.
PP, Pacific Plate; **RP,** Rivera Plate; **NAP,** North American Plate; **CP,** Cocos Plate; **GCRZ,** Gulf of California Rift Zone; **EPR,** East Pacific Rise; **MAT,** Middle America Trench; **MPFS,** Motagua-Polochic Fault System.
(c) Location of hydrothermal sites in Mexico.
(d) Simplified geologic map of Mexico. Different colors represent the main type of rock. Orange: felsic volcanic, grey: mafic volcanic, pink: metamorphic, plutonic and volcanics, green: carbonates, purple: evaporites and yellow: terrigenous sedimentary rocks.

SYNTHESIS AND DISCUSSION

All of this spatial information was compiled and categorized into spatial zones as shown in Figure 3. The country was divided into zones A through G based on the above criteria. Zones A and B are continental zones of exclusion, with zone G being the marine exclusion zone. Zones C, D and E are continental zones of inclusion, while zone F is the marine zone of inclusion. Table 1 shows the criteria considered in the selection of inclusion or exclusion zones. These inclusion zones are not yet ranked in terms of their storage potential; more information of the subsurface geologic structure is needed to assess the storage potential. Zone A is a zone of exclusion, where geologic carbon sequestration is not recommended. This zone includes igneous, metamorphic and volcano-sedimentary rocks, strong seismic activity and faults and active volcanic and hydrothermal features.

Zone B includes metamorphic, volcanic and volcano-sedimentary rocks, as well as some seismic activity, faults, volcanic features and frequent hydrothermal features. At this time it is also not recommended for geologic sequestration, though it has more future potential than Zone A.

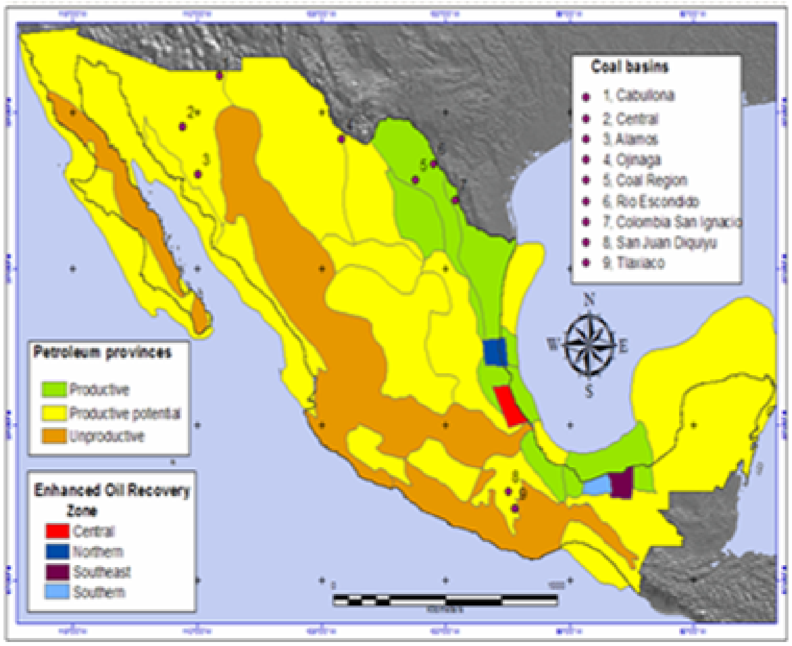

Figure 2. Map showing the petroleum provinces, coal basins and enhanced oil recovery zones. Source: (Santiago et al., 1984; USGS, 1997; CFE-GEIC, 2000 - 2009).

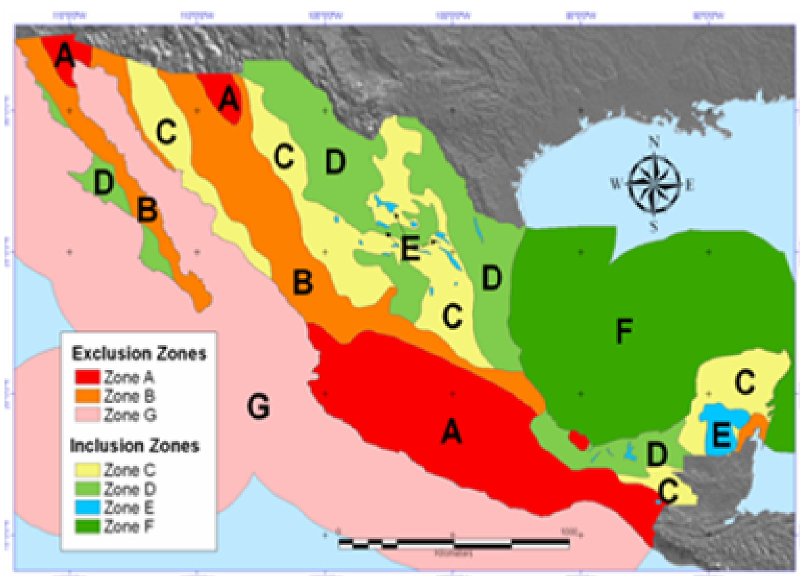

Figure 3. Zones of geologic carbon storage potential.
Zone A: red color, represents mostly igneous rocks with high seismic and volcanic hazard and is not recommended for storage.
Zone B: orange color, is also mostly igneous rocks with less seismic and volcanic hazards than zone A, but not recommended for storage at this time.
Zone C: yellow color, correspond to terrigenous and carbonate rocks.
Zone D: green color, is varying terrigenous sedimentary rocks.
Zone E: blue color, are evaporitic deposits and associated sedimentary rocks. Zone F: light blue color, are terrigenous and marine sediments beneath the Gulf of Mexico.
Zone G: is a marine zone of exclusion with terrigenous marine sediments and high seismic hazard and tectonic activity. Zones C through F, have little to no seismic and volcanic hazards and are recommended for further.

Table 1. Criteria selected to define the inclusion and exclusion zones involved in CO_2 geological storage. Numbers refer to the relative percentage based on surficial-level estimations. C: calcareous sequence, E: evaporitic sequences, MPV: metamorphic, plutonic and volcano-sedimentary series, T: terrigenous sequences, BV: mafic volcanic series, FV: felsic volcanic series. Active faults are considered those with movement recorded during the approximately last 10 000 years B.P. Active volcanoes are those with known historical eruptions as well as during Holocene times.

Main criteria		Type of rocks (%)						Large earthquakes (%) (1998 - 2009)	Enthalpy values (%)			Active faults (%)	Active volcanoes (%)
		C	E	MPV	T	BV	FV	Magnitude >5	High >220º	Medium 150 - 220 ºC	Low 90 - 150ºC		
Zones of exclusion	A	5	2	50	20	15	8	40	90	80	75	70	80
	B	5	0	20	10	5	60	0	5	10	20	20	20
	G	0	0	0	100	0	0	50	0	0	0	10	0
Zones of inclusion	C	30	20	3	35	2	10	3	5	10	5	0	0
	D	2	1	0	85	2	10	5				0	0
	E	0	100	0	0	0	0	0				0	0
	F	0	0	0	100	0	0	2	0	0	0	0	0

Zone C is a zone of inclusion, which should be studied further for potential storage sites. In the North it is characterized by continental clastic basins and volcanic rocks associated with elongated mountain ranges. There are also minor carbonate rocks and intrusive bodies. In the central-eastern section folded carbonates dominate, creating the hilly terrain. The South Eastern portion is dominated by calcareous rocks without significant folding, particularly at the Yucatan Peninsula. This zone has low seismicity and no definitive information about the presence of active faults.

Zone D is also a zone of inclusion recommended for further studies. It represents terrigenous rocks of varying age and depositional environments, mainly exposed as a basin or coastal marine deposits as well as fluvio-alluvial infill, with little to no seismic hazard or information on active faults. This zone has the best expectations due to the presence of abundant petroleum basins, oil and gas fields and enhanced oil recovery zones, as well as energy infrastructure facilities.

Zone E is a zone of inclusion and represents evaporitic deposits often associated with limestone, shale, sandstone, conglomerate and dolomite of different ages and origin with no seismic hazard or known active faults.

Zone F is the marine zone of inclusion, represents mainly recent clastic sediments in marine environments that fill the platforms and basins in the Gulf of Mexico. There is little to no seismic hazard and no clear information on active faults. Likewise zone D, it has potential storage in the deep marine oil fields.

Zone G is the marine zone of exclusion, not recommended for carbon storage. It is characterized by mainly terrigenous sediments deposited in recent marine environments at large depth and shows high seismic activity and active tectonics.

Conclusion

This represents a preliminary study on the geologic carbon storage opportunities in Mexico. By compiling volcanic, seismic, tectonic, geologic and lithologic information, we were able to define three zones of exclusion where geologic storage is not recommended: a zone in which geologic storage is not possible (Zone A), a zone in which geologic sequestration is not recommended (Zone B) and a marine zone where storage nor is it advisable (Zone G). We also defined four zones (C through F) which have potential for geologic storage and merit further research. We have created and updatable map, a tool for future studies of carbon storage potential in Mexico. This was a study of surface geology only and the completion of this more general, country-level stage of study has allowed CFE to begin investigation at basin- level of some specific deep sedimentary basins to characterize potential sites and storage capacity for Mexico.

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