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Research Paper

Appraisal of CO_2 storage potential in compressional hydrocarbon-bearing basins: Global assessment and case study in the Sichuan Basin (China)

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ABSTRACT

Carbon capture and storage (CCS) has been proposed as a potential technology to mitigate climate change. However, there is currently a huge gap between the current global deployment of this technology and that which will be ultimately required. Whilst CO_2 can be captured at any geographic location, storage of CO_2 will be constrained by the geological storage potential in the area the CO_2 is captured. The geological storage potential can be evaluated at a very high level according to the tectonic setting of the target area. To date, CCS deployment has been restricted to more favourable tectonic settings, such as extensional passive margin and post-rift basins and compressional foreland basins. However, to reach the adequate level of deployment, the potential for CCS of regions in different tectonic settings needs to be explored and assessed worldwide. Surprisingly, the potential of compressional basins for carbon storage has not been universally evaluated according to the global and regional carbon emission distribution. Here, we present an integrated source-to-sink analysis tool that combines comprehensive, open-access information on basin distribution, hydrocarbon resources and CO_2 emissions based on geographical information systems (GIS). Compressional settings host some of the most significant hydrocarbon-bearing basins and 36% of inland CO_2 emissions but, to date, large-scale CCS facilities in compressional basins are concentrated in North America and the Middle East only. Our source-to-sink tool allows identifying five high-priority regions for prospective CCS development in compressional basins: North America, north-western South America, south-eastern Europe, the western Middle East and western China. We present a study of the characteristics of these areas in terms of CO_2 emissions and CO_2 storage potential. Additionally, we conduct a detailed case-study analysis of the Sichuan Basin (China), one of the compressional basins with the greatest CO_2 storage potential. Our results indicate that compressional basins will have to play a critical role in the future of CCS if this technology is to be implemented worldwide.

1. Introduction

The cumulative anthropogenic CO_2 emissions to the atmosphere have produced an approximate 1 °C increase in global average temperature above pre-industrial levels (Peters et al., 2012; Masson-Delmotte et al., 2018). Serious concerns about global warming have recently been raised in the latest Intergovernmental Panel on Climate Change (IPCC) Report, which warns of the need to limit global warming to 1.5 °C to avoid catastrophic environmental damage (Masson-Delmotte et al., 2018). Achieving this target will require the combination of different approaches to climate change mitigation compatible with sustainable development, including CO_2 emission reductions. Carbon Capture and Storage (CCS) can be an efficient and safe method to meet these reductions (Metz et al., 2005; Scott et al., 2013; Alcalde et al., 2018; Bui et al., 2018; Global CCS Institute, 2018). However, there are only 44 large-scale CCS facilities under different development and operation status globally, with a combined CO_2 removal capacity of 83.41 Megatons of CO_2 per annum (Mtpa) (Global CCS Institute, 2019). Note that the current CCS development also includes CO_2 enhanced oil recovery (CO_2-EOR) projects, which can catalyse the implementation of CCS from

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economic aspects (Stewart and Haszeldine, 2014), but whose effect in the decarbonisation significance is unclear (e.g., Ettehadtavakkol et al., 2014; Armstrong and Styring, 2015; Hornafius and Hornafius, 2015). If the trend of CCS development continued, even considering CO_2-EOR projects, it would still be very far from the global decarbonisation targets (Koelbl et al., 2014; Bui et al., 2018; Global CCS Institute, 2018; Masson-Delmotte et al., 2018; Fig. 1), e.g., 348 Gigatons (Gt) based on a scenario with a broad focus on sustainability (Masson-Delmotte et al., 2018).

Kearns et al. (2017) estimated the global practically accessible geological storage capacity for CO_2 to be between 8000 Gt and 55,000 Gt, indicating that the storage capacity seems not to be a limiting factor for CCS deployment for the rest of this century for most regions. However, storage capacity is not the only parameter that determines a region's suitability for CCS. Other factors include the tectonic setting, basin architecture, reservoir quality, caprock sealing capacity, depth, geothermal gradient, reservoir pressure, hydrogeology, and other environmental and economic factors (Bachu, 2003; Wei et al., 2013; Edlmann et al., 2015).

In particular, the tectonic settings under which a targeted basin was formed exert a significant effect on the other factors listed above (Edlmann et al., 2015; McDermott et al., 2017). Tectonic settings are broadly split into compressional, extensional and strike-slip categories that reflect the relative plate motions that determine their past and present stress state. Despite being ubiquitous in all continents, the potential of compressional basins to safely store captured CO_2 has not been systematically studied, especially in terms of comparison between their storage capacity and the demand for storage, which is directly determined by the geographic distribution and volume of carbon emissions. The present study aims to critically close this knowledge gap by providing a global assessment on the role of compressional basins in the future of global CCS.

Compressional basins are generally formed by the collision and subduction of tectonic plates and can also form within plates, and are characterized by shortening and deformation of the lithosphere. We consider here the two most common types of compressional basins: peripheral foreland basins, developed adjacent to mountain belts, and retro-arc foreland basins, developed adjacent to island volcanic arcs. Compressional basins tend to develop in tectonically active areas and experience faulting and folding, raising the risk of CO_2 leakage (Bachu, 2003). Compared to other basin types, such as those developed under extensional or strike-slip tectonic regimes, compressional basins present in some cases lower geothermal gradients because of the cooling effect of the relatively cold subducting plate (Edlmann et al., 2015). This results in lower reservoir temperature and higher CO_2 density, and further leads to high storage capacity and low buoyancy force due to lower density contrast between CO_2 and formation fluids (Bachu, 2003; Miocic et al., 2016; Iglauer, 2018). Moreover, compressional basins also typically present higher fluid pressure and lower risk of CO_2 leakage owing to their much higher minimum principal stress (Wei et al., 2013), compared with other basin types. Using geomechanical facies assessments, Edlmann et al. (2015) ranked peripheral foreland basins as the most suitable sites for CO_2 storage, followed by passive continental margins, rift and strike-slip basins. These results indicate that compressional basins, and more especially foreland basins, have great potential for CCS development.

Mann et al. (2003) studied 877 giant fields worldwide, observing that 27.83% of them are located in compressional settings. Tian et al. (2014) pointed out that 20.46% of globally undiscovered conventional hydrocarbon resources are stored in foreland basins. Abundant hydrocarbon resources are stored in compressional basins, especially concentrating in the Middle East, North America, South America, Central Asia, and China (Tian et al., 2014; Wang et al., 2016; Tong et al., 2018). Hydrocarbon-bearing provinces are the primary targets of CCS because of proven sufficient capacity and suitable characteristics to trap and store fluids over long periods of time and a substantial number of geological datasets and host industrial infrastructures with potential for re-use for CCS development (Godec et al., 2011; Kuuskraa et al., 2013; Alcalde et al., 2019).

However, it should be noted that the properties of hydrocarbons are different than those of CO_2, such as the physical-chemical processes (e.g., interfacial tension, wettability, density), their flow dynamics and the associated risks when these fluids are in the subsurface (Chiquet et al., 2007; Naylor et al., 2011; Alcalde et al., 2018; Miocic et al., 2019). Therefore, it must take care when using hydrocarbon reserves as a proxy for CO_2 storage potential. In this sense, we use hydrocarbon volume only as a proxy to quantify and rank CO_2 storage potential of these hydrocarbon-bearing basins, rather than using them as a quantitatively equivalent to storable CO_2 emissions. A detailed site characterisation is still needed to assess the storable CO_2 emissions and the potential security of a chosen hydrocarbon reservoir, case by case.

To date, large-scale CCS facilities in compressional basins are concentrated in North America and the Middle East. China and Europe account for significant proportions of global CO_2 emissions and host large compressional basins that could be used for CO_2 storage. However, there are currently no large-scale CCS facilities in operation or even under consideration in these basins, indicating that the potential of these regions still needs to be explored. Despite their promising prospect, the potential of compressional basins has not been assessed quantitatively and in detail to date. Global and regional assessments of CO_2 storage potential are critical to identify short- to middle-term prospects, which can become primary targets for the development of a CCS industry in high priority/high need regions. The overarching aim of this study is to reveal the role of compressional basins and evaluate how appropriate storage regions that developed in compressional settings are for CCS

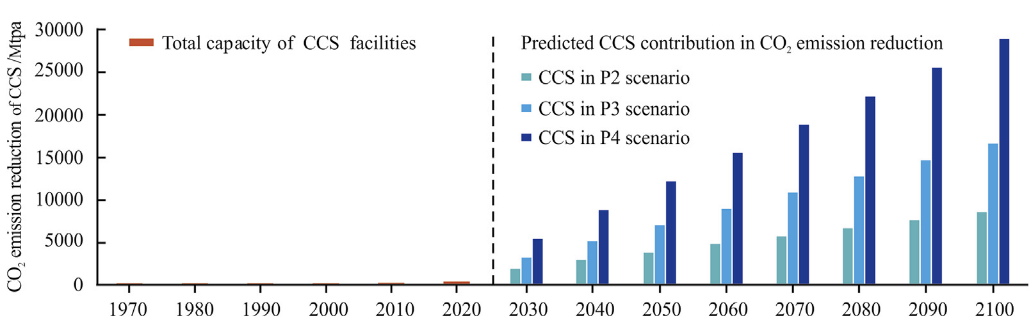

Fig. 1. Total capacity of CCS facilities (data source Global CCS Institute, 2019) and predicted CCS contribution in CO_2 emission reduction (in Mtpa) according to different IPCC Special Report on Global Warming of 1.5 °C scenarios (namely P2, P3 and P4). P2 is a sustainability-oriented scenario where emission reductions are mainly achieved by high human and low-carbon technology development, and low demand in energy and products; P3 is a middle-of-the-road scenario where emission reductions are mainly achieved by changing the ways energy is produced and products are manufactured, and to a lesser degree by demand reductions; P4 is a resource- and energy-intensive scenario where emission reductions are mainly achieved through technological means, making strong use of carbon dioxide removal through the deployment of bioenergy with CCS) (Global CCS Institute, 2018; Masson-Delmotte et al., 2018).

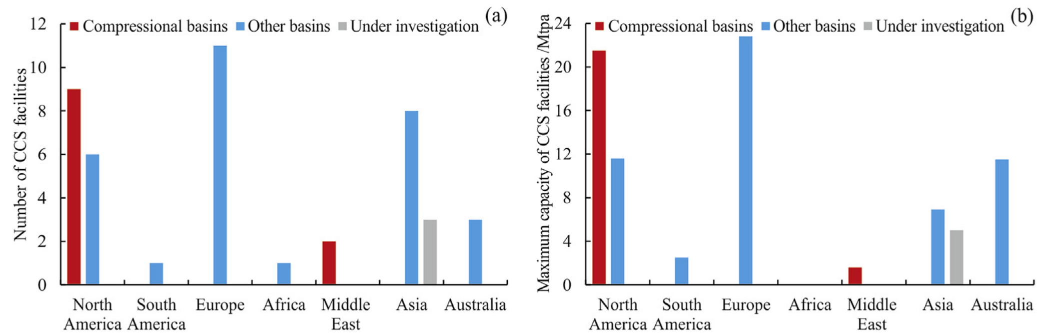

Fig. 2. (a) Number of large-scale CCS facilities and (b) capture and injection capacity (in Mtpa) in different regions of the world (data source Global CCS Institute, 2019). Grey bars represent CCS facilities whose storage sites and transportation methods are still under investigation.

development.

In this contribution, we analyse the spatial distribution of the main hydrocarbon-bearing basins in the world and compare their potential reservoir capacity with global CO_2 emissions using GIS methods. Based on previous source-to-sink appraisals (e.g., UNIDO, 2011; Edlmann et al., 2015), we adopt updated CO_2 emissions, comprehensively consider tectonic settings of basins and projected emission reductions of countries and, finally, create an integrated parameter to identify regions with high CO_2 storage potential in compressional basins. This detailed analysis allows us to evaluate to what extent compressional basins represent the best CCS option in certain regions, and whether they can play an essential role in global CCS development.

2. Current status of CCS in compressional basins

According to the latest data from the CCS Facilities Database (Global CCS Institute, 2019), there are 44 large-scale CCS facilities under different development and operation status, able to capture and inject at most 83.41 Mtpa of CO_2, once they are all fully functional (Fig. 2a and b). By number of facilities, most CCS activity is located in North America, Europe and Asia, with 15, 11 and 11 facilities, respectively. If measured by the capacity for CO_2 capture and injection, activity concentrates in North America, Europe, Asia and Australia, with 33.1, 22.8, 11.91 and 11.5 Mtpa, respectively. Global CCS development is hence far from achieving the CO_2 emission reduction targets set for 1.5 °C above pre-industrial levels (Masson-Delmotte et al., 2018).

CCS development in compressional basins shows a heterogeneous distribution to date (Fig. 2). There are currently eleven large-scale CCS facilities located in compressional basins, while there are 30 facilities in other basin types. The large-scale CCS facilities in compressional basins can capture and inject 23.1 Mpta of CO_2, accounting for 27.7% of all large-scale facilities globally. However, they are nearly all in North America with nine facilities that can capture and inject 21.5 Mpta of CO_2, with another two facilities and storing 1.6 Mpta of CO_2 in the Middle East. Furthermore, 90% of these facilities are enhanced oil recovery projects (CO_2-EOR), and therefore not fully dedicated to storage. Most regions do not host any large-scale CCS facilities either in operation or even under consideration. In the following sections, we investigate the characteristics of global compressional basins to identify areas with potential for CCS development.

3. Data and methods

3.1. Basin resources and CO_2 emission data

Suitable storage options include oil and gas fields, unconventional reservoirs, basaltic rocks and deep saline aquifers (Metz et al., 2005; Bachu, 2007; Matter et al., 2009). Oil and gas fields are likely targets for CCS because of their proven capacity to safely retain fluids over geological timescales. Furthermore, substantial subsurface data, as well as infrastructure in place suitable for re-use, are usually available from exploration and production activities (Alcalde et al., 2019). Although unconventional reservoirs show potential for CCS development and even resulted in recent CCS project evaluation and implementation, especially in coal seams and shales (Bachu, 2007; Kang et al., 2011; Liu et al., 2013), there are still noticeable uncertainties and risks due to their heterogeneous and tight characteristics. Basaltic rocks facilitate the transformation of CO_2 to carbonate minerals, referred to as mineral trapping, owing to their high reactivity and abundant metal ions, but this option is only very recent and it is still being investigated (Gislason and Oelkers, 2014). Saline aquifers and oil and gas fields are the most developed storage types because of the large potential capacity and the data availability respectively. However, the subsurface data that characterise global saline aquifers is more sparse and incomplete than in oil and gas fields, so we restrict our assessment to hydrocarbon-bearing basins.

Based on data from the National Petroleum Assessment and the World Petroleum Assessment of the United State Geological Survey (USGS) (USGS, 1995–2013, 2000; Bird et al., 2008), we obtained global basin shapes and values for conventional hydrocarbon resources of more than 200 basins (Fig. 3a). The total hydrocarbon resources utilized here consist of the cumulative hydrocarbon production, remaining recoverable hydrocarbon and undiscovered recoverable hydrocarbon estimated to exist based on geological knowledge and theory (USGS, 2000). Since the USGS only provides data on undiscovered resources for the United States (USGS, 1995–2013), we deduced their total resources using the ratio of undiscovered vs total resources of global basins (USGS, 2000). For most basins in the Arctic Circle, which have not experienced extensive exploration and development, undiscovered resource estimates are assumed to match their total resource estimates (Bird et al., 2008).

Based on the CGG Robertson Sedimentary Basins compilation (Robertson, 2014), we have divided global hydrocarbon-bearing basins into five major tectonic settings: foreland basins, passive margin basins, intracratonic basins, rift and post-rift basins, and other basins (Fig. 3b). Over 40% of hydrocarbon-bearing basins by area are located in foreland basins, which mainly concentrate in six regions (Fig. 3a and b): North America, West South America, East Europe, West Middle East, central Asia and China.

The global stationary CO_2 emissions in 2012 were extracted from the version v4.3.2 of the Emissions Database for Global Atmospheric Research (EDGAR) (EDGAR, 2018; Janssens-Maenhout et al., 2019) (Fig. 4). We use emission sources in 2012 to identify areas of high stationary emissions, assuming that these areas will require greater mitigation efforts. The dataset includes CO_2 emissions from various resources, including population, energy, fossil fuel consumption and production, agriculture, industry, and solid and liquid waste. Our current technological level does not allow us to capture small and dispersed CO_2 emissions, such as those associated with transport or agricultural activities. Thus, we have only considered emission points above 10,000 tons of CO_2 per annum (tpa), which add up to 32.72 Gt globally, constituting the 97% of the global total emissions (34.87 Gt; EDGAR, 2018).

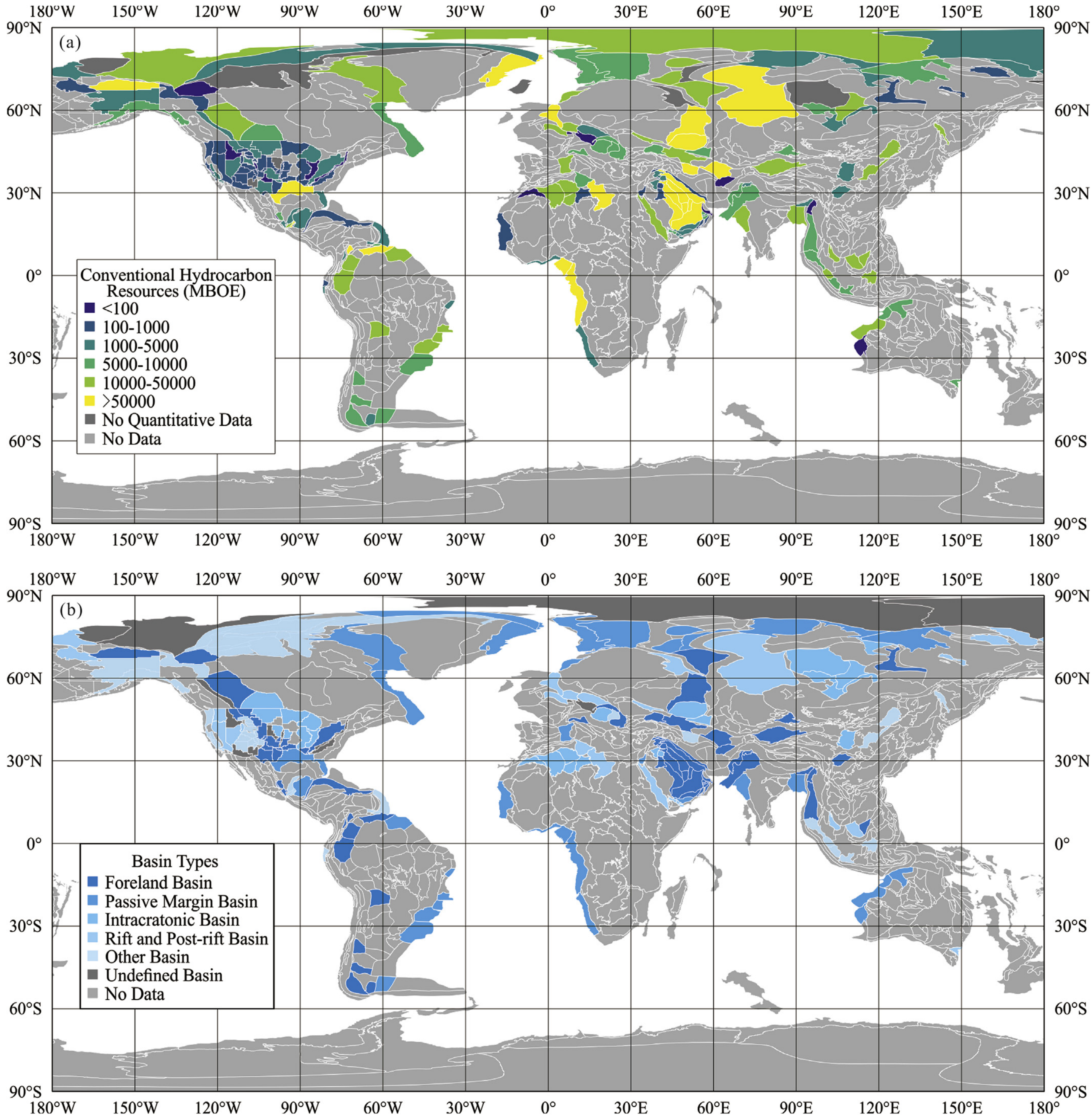

Fig. 3. Distribution of (a) major conventional hydrocarbon resources (given in million barrel of oil equivalent (MBOE)): basins in the United States (USGS, 1995–2013), the Arctic Circle (Bird et al., 2008) and other regions (USGS, 2000) and (b) the tectonic settings of main hydrocarbon-bearing basins (Robertson, 2014).

Finally, we have used the Projected Emission Reductions (PER) plans by 2030 that different G20 economies signed according to the unconditional Intended Nationally Determined Contributions (INDCs) scenario (Fig. 5) (Den Elzen et al., 2016). We assume that countries with high PER have greater urgency for addressing climate change mitigation, and thus CCS will be more likely to be implemented in them. These unconditional INDCs are not directly comparable, since different economies submitted their INDCs in various forms. For example, some countries provided baseline emission projections in INDCs while others did not. Moreover, China and India have proposed a combination of targets, which need to be calculated using their respective energy models (Den Elzen et al., 2016). Den Elzen et al. (2016) compiled these datasets and produced a unified and comparable dataset. However, since 2016, some of the G20 countries considered have changed their emission reduction plans. For example, the USA announced that they withdraw from the Paris Agreement, and its Nationally Determined Contribution was rated "Critically Insufficient" by the Climate Action Tracker (Climate Action Tracker, 2018). Furthermore, our focus on G20 countries does not imply that other countries do not have their own emission reduction plans. Thus, the data from Den Elzen et al. (2016) is not necessarily in line with the current climate policies, but offer a unified framework for comparison across countries.

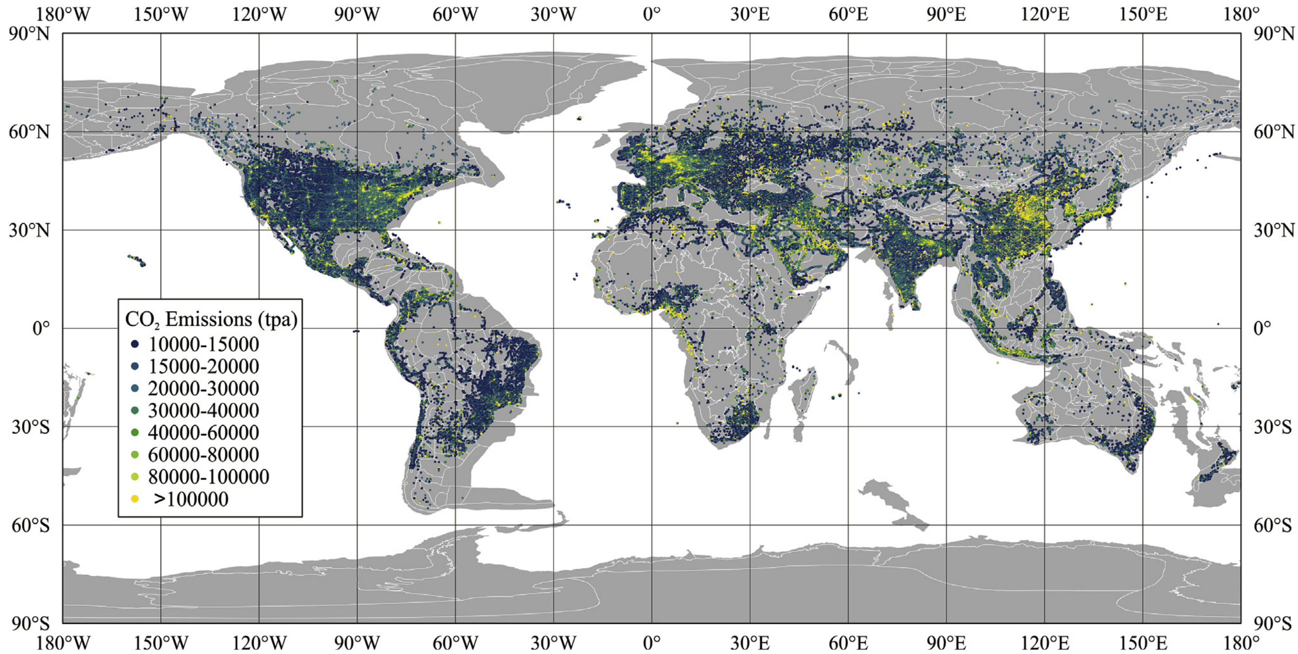

Fig. 4. Distribution of CO_2 emissions (tons per annum (tpa)) (data source EDGAR, 2018).

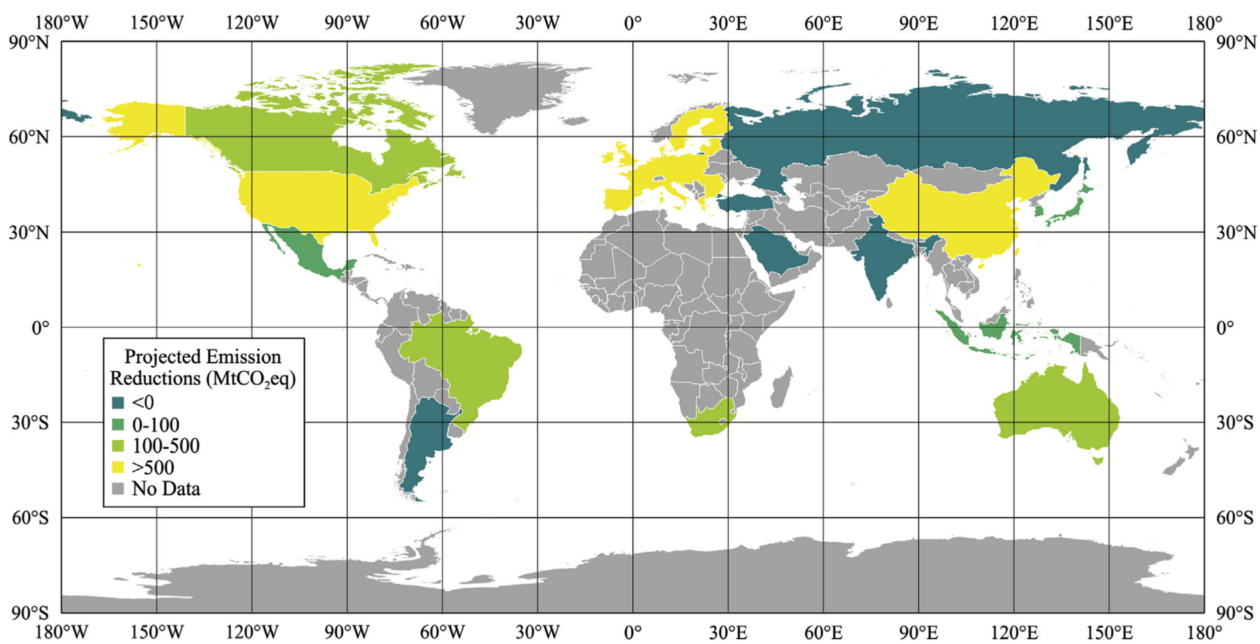

Fig. 5. Projected emission reductions in 2030 of G20 economies (Million tonnes CO_2 equivalent ($MtCO_2eq$)) (data source Den Elzen et al., 2016).

3.2. Data processing in GIS software

We have combined the three datasets (i.e., basin distribution, basin hydrocarbon resources and CO_2 emissions) to develop a source-to-sink matching approach. This process allows us to correlate the distribution of CO_2 emissions with the available storage space in compressional basins, using hydrocarbon resources as a proxy.

First, we input the basin polygon shapes and localised the CO_2 emission points into a GIS-based software (QGIS version 3.4.2, 2018). To delimit and calculate the combined CO_2 emissions in each basin, we summed all the CO_2 emissions lying within each basin (Fig. 6). As long distances between CO_2 sources and sinks (i.e., emission points and basins) can increase the transport and monitoring costs, making CCS financially unattractive, we only considered CO_2 emission points lying within the target basins and disregarded all other emission sources.

For the storage potential appraisal, we assume that compressional regions with high potential for developing CCS must encompass sufficient hydrocarbon resources and CO_2 emissions. Due to the difference in magnitude between hydrocarbon resources (V_H) and CO_2 emissions (V_{CO_2}), data processing is necessary before the selection of potential regions. We applied a data normalization based on a function of their minimum and maximum values:

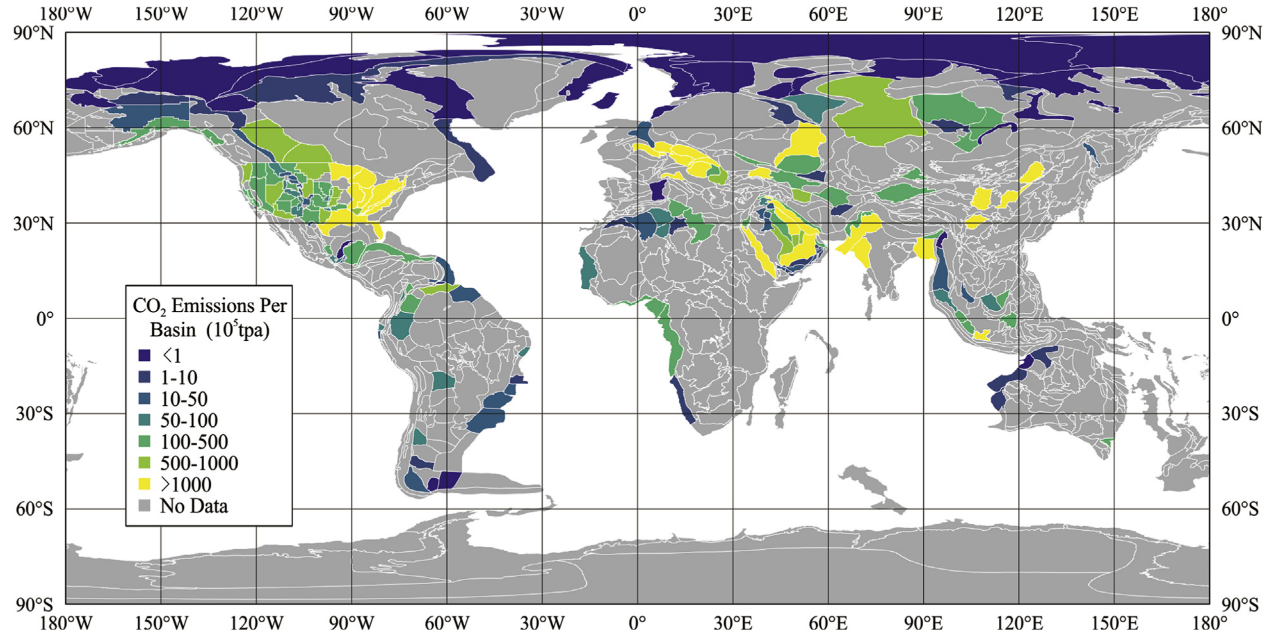

Fig. 6. Distribution of potential CO_2 emissions (in 10^5 tpa) within the main hydrocarbon-bearing basins. Only emission points above 10^4 tpa are considered in this study.

$$V_n = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \tag{1}$$

where V_n, V, V_{min} and V_{max} are the normalized value, the actual value, the minimum value and the maximum value, respectively.

We created an integrated evaluation parameter ($V_{CCS\text{-}P}$) to evaluate basin potential for CO_2 storage:

$$V_{CCS-P} = V_{nH} \times V_{nCO_2} \tag{2}$$

where V_{nH} and V_{nCO_2} are the normalized values of V_H and V_{CO_2}, respectively.

Hydrocarbon resources are not quantitatively equivalent to storable CO_2 emissions, which require more geological parameters to be calculated (Goodman et al., 2011). Hence, we use hydrocarbon resources only as a proxy to quantify and rank CO_2 storage potential of these hydrocarbon-bearing basins. Finally, we obtained the distribution of $V_{CCS\text{-}P}$ that highlights basins with high (yellow) and low (blue) potential for CCS (Fig. 7a) and identified five high-priority regions that have high $V_{CCS\text{-}P}$ and are dominated by compressional basins (Fig. 7b).

4. Results and discussion

4.1. CO_2 storage potential in compressional basins

The hydrocarbon industry has abundant oil and gas resources stored in compressional basins, indicating their significant potential for CCS. Our GIS analysis relates the storage capacity of basins with the potential demand for carbon storage, according to the geographic distribution and volume of CO_2 emissions.

The total hydrocarbon resources in global compressional basins reach over 2184 billion barrels of oil equivalent (BBOE), accounting for around 50% of the total resources in all hydrocarbon-bearing basins. Compressional basins also contain significant CO_2 emission sources, with 3.8 Gt of CO_2 annual emissions accounting for 34% of all hydrocarbon-bearing basins. Compressional basins with high CO_2 emissions are mainly located in Western Canada, America, the Middle East, Europe and China (Fig. 6).

To select the target areas with the greatest CO_2 storage potential in compressional basins, which will be taken forward for detailed assessment, we favoured the areas with high $V_{CCS\text{-}P}$ compressional basins that are also relatively isolated from other basin types for prospective CCS storage. Based on the distribution of $V_{CCS\text{-}P}$, we have selected five high-priority regions for detailed assessment (Figs. 7 and 8): (1) North America, (2) north-western South America, (3) south-eastern Europe, (4) western Middle East, and (5) western China. Of the five high-priority regions, only North America, Europe and China have explicit high-emission reduction targets in place (Den Elzen et al., 2016) (Fig. 7c), and therefore they are more likely to implement decarbonisation actions, like CCS.

4.2. High-priority regions

4.2.1. North America

The area spreads across the USA and western Canada and is composed of 17 compressional basins adjacent to the Rocky Mountain, Marathon-Ouachita and Appalachian fold-and-thrust belts (Fig. 7b), which formed owing to the closing of ocean between Laurasia and Gondwana in the Late Paleozoic and the collision between the North American and Pacific plates during the Meso–Cenozoic (Ma et al., 2014).

These basins have 11 BBOE of undiscovered conventional hydrocarbon resources and 26.5 BBOE of estimated total hydrocarbon resources, mainly distributed in the Western Canadian Sedimentary Basin (WCSB), the Permian Basin, the Appalachian Basin and the Montana Thrust Belt. In this area, the major CO_2 sources relate to electricity generation in Canada and electricity, refinery, chemical and other hydrocarbon industries in the USA (U.S. Department of Energy Office of Fossil Energy, 2015). Around 1180 Mtpa of CO_2 emissions are distributed in compressional basins, mainly in the Appalachian Basin, the Bend Arch-Fort Worth Basin and the WCSB.

The USA and Canada account for 11.85% and 1.92% of global greenhouse gas emissions in 2012, respectively (Den Elzen et al., 2016). Their high emission reduction targets (Den Elzen et al., 2016) (Fig. 8) and high suitability for CCS development (Mitrovic et al., 2011; Blondes et al., 2013) have made this region the most active area of CCS development worldwide (Global CCS Institute, 2018). There are nine large-scale CCS facilities in operation or under advanced development in the target compressional basins that can capture and inject at most 21.5 Mtpa of CO_2, dominating the global CCS development in compressional

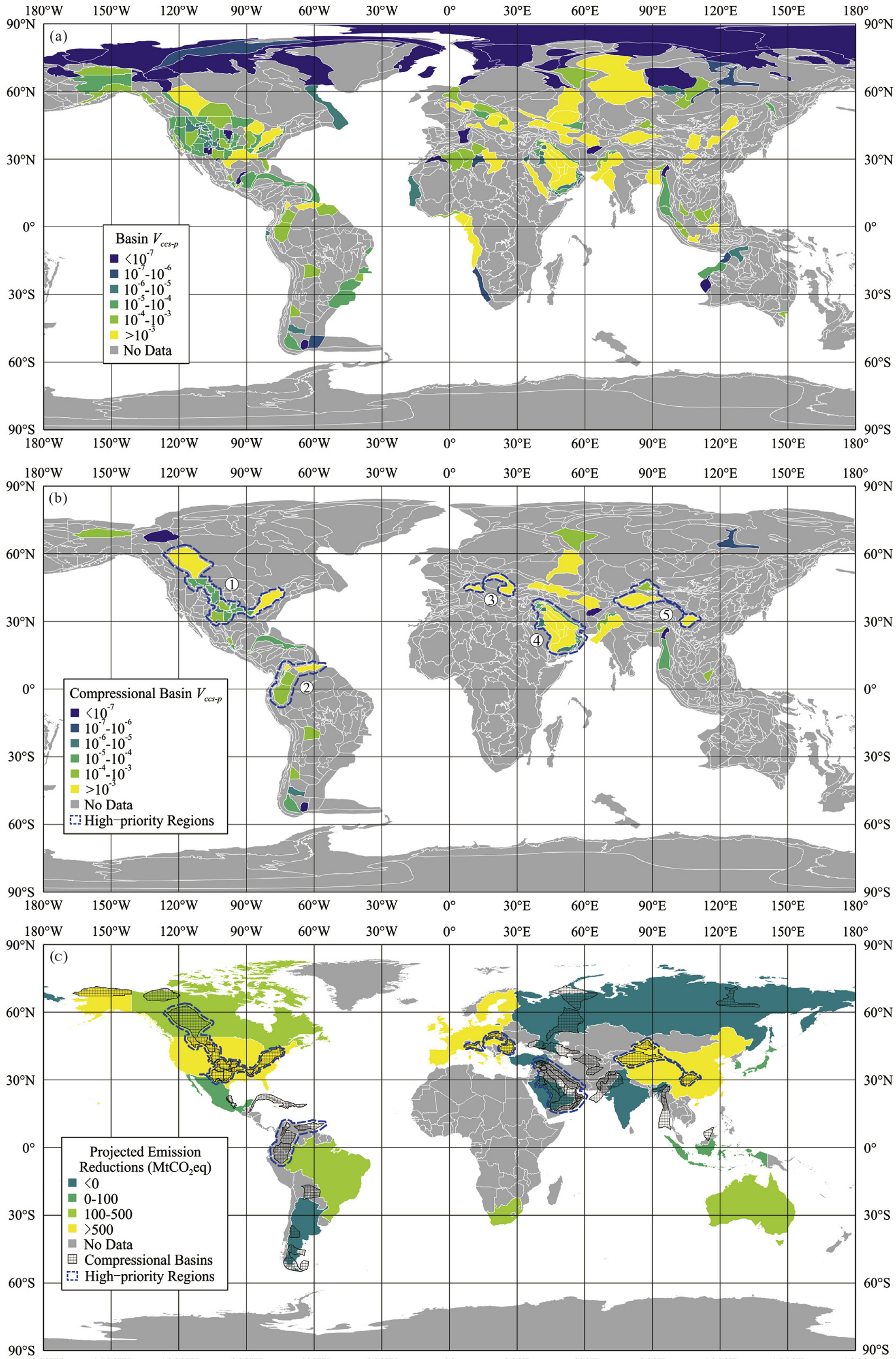

Fig. 7. Distribution of the integrated evaluation parameter (V_{CCS-P}) in (a) the main hydrocarbon-bearing basins in the world; (b) V_{CCS-P} in compressional hydrocarbon-bearing basins; and (c) distribution of the high-priority regions and the projected emission reductions of G20 economies (data source Den Elzen et al., 2016). The numbers in (b) and (c) mark the high-priority regions selected for detailed analyses: (1) North America; (2) north-western South America; (3) south-eastern Europe; (4) western Middle East; (5) western China.

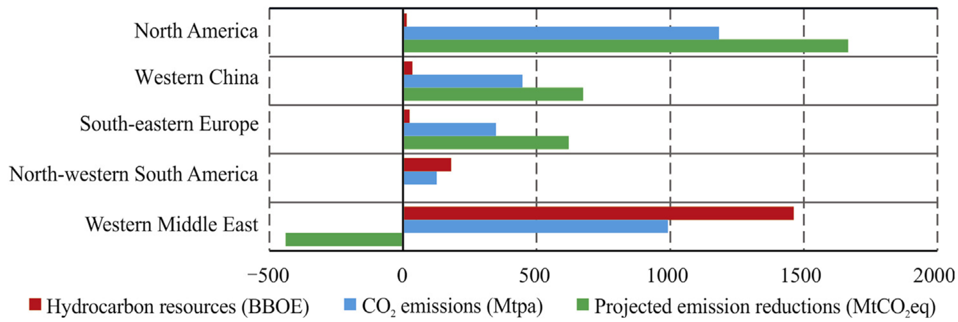

Fig. 8. Comparison of hydrocarbon resources (BBOE) (only the undiscovered resources are attainable for North America), CO_2 emissions (Mtpa) and projected emission reductions ($MtCO_2eq$) of the selected high-priority regions (Only the PER of the western Middle East is negative).

settings. According to the distribution of $V_{CCS\text{-}P}$ value, the compressional basins with the highest potential are the WCSB and the Appalachian Basin. The CO_2 emissions from the large-scale facilities in the WCSB (the Alberta Carbon Trunk Line and the Quest) derive mainly from fertiliser production, oil refining and hydrogen production (Global CCS Institute, 2019). Only two pilot and demonstration CCS facilities have been developed in the Appalachian Basin, the Marshall County ECBM Project (Wilson et al., 2012) and the Mountaineer Validation Facility (Mishra et al., 2014), both closed in the 2010's with around 40,000 t CO_2 stored in the subsurface.

4.2.2. North-western South America

Owing to the subduction of the Pacific and Caribbean plates under the South American Plate after the Late Cretaceous, fore-arc basins, the Andes and retro-arc foreland basins developed from offshore to inland in western and northern South America (Xie et al., 2009; Yang et al., 2009). Retro-arc foreland basins dominate hydrocarbon resources in north-western South America (Yang et al., 2009), which are regarded as the main CCS targets located in Peru, Ecuador, Colombia and Venezuela (Fig. 7b).

North-western South America has 178 BBOE of hydrocarbon resources, mainly distributed in Venezuela. On the other hand, CO_2 emissions are mainly outcomes from power generation, cement and refinery industries in west South America, accounting for 46%, 24% and 18% of the emissions, respectively (UNIDO, 2011). These compressional hydrocarbon-bearing basins in North-western South America contain 123 Mtpa of CO_2 emissions.

Colombia and Venezuela are the main CO_2 emitters in the region, accounting for around 0.5% of global greenhouse gas emissions in 2012, which aim to achieve emission reduction targets of 20% below business as usual level by 2030 (Den Elzen et al., 2016). Although there are no large-scale CCS facilities under operation or construction, other decarbonisation measures (e.g., enhancing energy efficiency, substituting energy-intense appliances with more efficient models) have been effectively applied in the region (Pereira et al., 1997; Román et al., 2018). The high potential for CCS of the region, marked by its $V_{CCS\text{-}P}$, may facilitate CCS development in the future. In particular, the East Venezuela Basin contains some of the largest oil accumulations in the world (Erlich and Barrett, 1992), a long history of production and suitability for CO_2-EOR (Manrique et al., 2003), which can open the door to a CCS industry in the area.

4.2.3. Southeastern Europe

The compressional setting in this region is closely related to the Alpine Orogeny, originated by the convergence of the African and European plates after the closing of the interposed Tethys Ocean (Castellarin, 2001). Three compressional basins with high CO_2 storage potential are located in southern and eastern Europe, the North Carpathian, Carpathian-Balkanian and Po basins (Fig. 7b), which mainly belong to Romania, Bulgaria, Poland, Ukraine and Italy. These three basins contain 21 BBOE of hydrocarbon resources and host activities emitting 344 Mtpa of CO_2 per year. CO_2 emissions are mostly produced from power generation, cement and refinery industries, accounting for 71%, 14% and 10% of the total emissions in these industries in south-eastern Europe, respectively (UNIDO, 2011).

The European Union countries are the third largest CO_2 emitter globally (www.globalcarbonatlas.org), and therefore have been urged to assume important emission reductions (e.g., 20% reduction by 2020) (da Graça Carvalho, 2012) and 40% by 2030 compared to 1990 (deLlano-Paz et al., 2016), which equal to more than 600 $MtCO_2eq$ (Den Elzen et al., 2016). Within these scenarios, CCS must be invoked in order to meet their CO_2 reduction targets (Vangkilde-Pedersen et al., 2009). Despite new initiatives are mainly concentrated in Norway, the UK and the Netherlands (Neele et al., 2017), the Carpathian region shows great storage potential and has drawn some attention for CCS development, particularly in Poland (Uliasz-Misiak, 2007; Radoslaw et al., 2009), which is a major coal producer in Europe. CCS could help in the transition to cleaner energy production systems while reducing the economic impact of this transformation (Odenberger et al., 2013).

4.2.4. Western Middle East

In this region, the foreland basins formed from the Cretaceous to the Miocene because of the subduction of the Arabian Plate under the Eurasian Plate (Mohajjel et al., 2003; Wang, 2012). These basins experienced transpression during the Pliocene, which superposed on previous passive margin and faulted basins (Wang, 2012). This area contains the greatest enrichment of hydrocarbon resources in the world. All these resources (1458 BBOE) are hosted in compressional basins, mainly distributed across the Zagros Fold Belt, the Rub Al Khali Basin, the Greater Ghawar Uplift and the Mesopotamian Foredeep Basin. The CO_2 emissions in this area (988 Mtpa) mainly result from power generation and refinery activities, which take up 64% and 16% of all CO_2 emissions of the Middle East (UNIDO, 2011).

The Middle Eastern INDCs are generally quite low. For example, CO_2 emission reductions in Iran, Iraq and Oman are 4%, 1% and 2% respectively, and countries such as the United Arab Emirates and Qatar have not committed to quantitative targets (Den Elzen et al., 2016). Saudi Arabia even has negative projected emission reductions relative to the current policy scenario in 2030 (Den Elzen et al., 2016) (Fig. 8). However, the availability of giant hydrocarbon fields in the area offers significant potential for CCS development, especially for CO_2-EOR projects (Algharaib, 2009). There are two large-scale CCS facilities operating for enhanced oil recovery, the Uthmaniyah CO_2-EOR Demonstration in Saudi Arabia and the Abu Dhabi CCS, whose capture capacities are both 0.8 Mtpa with CO_2 emissions resulting from natural gas and steel industries (Global CCS Institute, 2019).

4.2.5. Western China

Compressional settings in western China are controlled by the collision of the Indian and Eurasian plates and are closely related to the

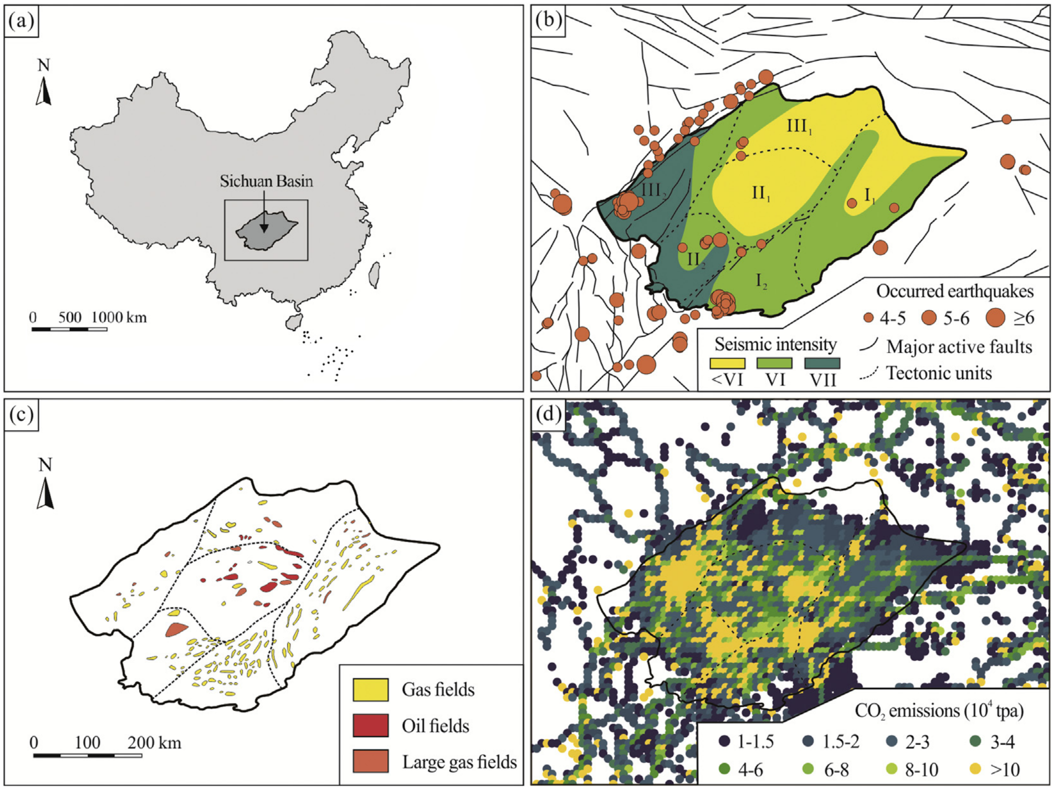

Fig. 9. (a) Geographical location, (b) tectonic units (the Eastern High-steep Fold Belt (I_1), the Southern Low-steep Fold Belt (I_2), the Central Gentle Fold Belt (II_1), the South-western Low-steep Fold Belt (II_2), the North-western Low-flat Fold Belt (III_1) and the Western Low-steep Fold Belt (III_2)) (Diao et al., 2017b), major active faults, seismic intensity (Wei et al., 2013), occurred earthquake from 2012 ($\geq$4 magnitude) (data source China Earthquake Networks Centre, 2019), (c) oil and gas fields (Ma et al., 2010) and (d) CO_2 emissions ($\geq$10,000 tpa) (data source EDGAR, 2018) of the Sichuan Basin.

evolution of the Tethys Ocean (Jia et al., 2003; Song et al., 2015). The main hydrocarbon-bearing basins include the Sichuan, Tarim and Junggar basins, which store 33.6 BBOE of conventional hydrocarbon resources. CO_2 emissions mainly result from cement, power plants, ammonia and steel industries (Li et al., 2009; Wei et al., 2013). Furthermore, compressional basins have 445 Mtpa of CO_2 emissions, dominated by the Sichuan Basin accounting for 87% of the total emissions.

As the second largest energy consumer and the largest carbon emitter, there is an urgent need for carbon emission reductions in China, with 671 Mt of CO_2 emissions to be reduced by 2030 compared to the current policy scenario (Den Elzen et al., 2016). CCS has been regarded as one of the essential actions for climate change mitigation (Li and Huang, 2010; Zhang et al., 2013). It has been evaluated that the Tarim, Junggar and Sichuan basins have high suitability for CCS (Wei et al., 2013; Guo et al., 2015). However, the nine large-scale CCS facilities that are in operation or in construction in China to date are located outside these basins, as most western basins (e.g., the Tarim and Junggar basins) are located relatively far away from the main industrial areas than eastern basins in China. The Sichuan Basin, on the other hand, with its relatively high hydrocarbon reserves and high CO_2 emissions, deserves more attention for CCS in China. Accordingly, we present here a more detailed analysis of the Sichuan basin and evaluate the opportunity that it represents for the future development of CCS in this region.

4.3. Case study: Sichuan Basin

Regions must satisfy several requirements to be considered suitable for CCS. These requirements are related to the characteristics of the storage site (i.e., tectonic activity, geo-temperature, pressure), the reservoir (i.e., volume, porosity, permeability), the caprock (sealing capability), and other economic and social aspects (e.g., source of CO_2, industrial infrastructures, policy support) (Bachu, 2003; Wei et al., 2013; Leung et al., 2014). In this respect, the Sichuan Basin presents a high $V_{CCS\text{-}P}$ and is located in China, a country with a high PER and therefore prospective decarbonisation plans. This basin is used here to illustrate the potential of compressional basins for CCS development from the above aspects.

The Sichuan Basin, located in SW China (Fig. 9a), is a typical superimposed basin (Ma, 2017a) that was developed during the Middle and Late Proterozoic, with the Yangtze Platform forming its basement. The Sichuan Basin developed in extensional settings before the Early Triassic, and was inverted into compressional settings due to the closing of the Paleo-Tethys Ocean and the collision between the oceanic crust and the Yangtze Platform, and accordingly formed a foreland basin in the Late Triassic and Jurassic. Since then, intense folding and erosion have constantly shaped the Sichuan Basin (Mao et al., 2006), currently surrounded by peripheral orogenic belts and a series of fold-and-thrust belts. The geothermal gradient in the Sichuan Basin generally ranges of 20–25 °C/km (Wang et al., 2011), resulting in higher storage capacity and lower buoyancy force than warmer basins (Bachu, 2003; Wei et al., 2013). The Sichuan Basin can be divided into six secondary tectonic units, among which, the Southern Low-steep Fold Belt (region I_2), the South-western Low-steep Fold Belt (II_2) and the Western Low-steep Fold Belt (III_2) have complicated tectonic background, with relatively high seismic intensity and more developed active faults, which may be responsible for the large number of earthquakes occurred (China Earthquake Networks Centre, 2019; Fig. 9b). On the other hand, the Central Gentle Fold Belt (II_1) has a relatively stable crust with low seismicity, making it is suitable for CO_2 storage (Fan et al., 2014) (Fig. 9b). It has an area of 37,000 km^2, which corresponds to a large basin according to the CCS evaluation criteria of Wei et al. (2013). Finally, the Eastern High-steep Fold Belt (I_1)

and the North-western Low-flat Fold Belt (III_1) have moderate tectonic environments.

The Sichuan Basin has the largest reserves and the second largest production of natural gas in China (Ma, 2017a). The latest data indicate that there are 12.5 trillion cubic meters of conventional natural gas resources (Ma, 2017b) and 81.2 million tons of oil (Luo et al., 2013). Hydrocarbon resources are mainly distributed in the Permian and Triassic units, and oil is mainly lying in the central Sichuan Basin, while natural gas is mainly stored in the eastern Sichuan Basin (Ma et al., 2010; Ma, 2017b) (Fig. 9c). All these hydrocarbon resources and fields indicate the significant potential of the Sichuan Basin for CCS. First, it has qualified reservoirs and caprocks which provide significant capacity to store and seal fluids over long periods of time. It is estimated that the Sichuan Basin can store 5.45 Gt or 3.41 Gt of CO_2 in hydrocarbon fields based on the methods of depleted hydrocarbon fields or enhanced hydrocarbon recovery, respectively (Diao et al., 2017a). Since oil and gas exploration and production in the Sichuan Basin started in 1953 (Zhang and Zhang, 2002), abundant boreholes, seismic data and other geological data provide prerequisites for CCS development. Finally, the Sichuan Basin has the most advanced and mature technology of the natural gas industry in China, including equipment, infrastructure, technology and research systems (Ma, 2017b). For instance, the total length of gas pipeline exceeds 4000 km with more than 50×10^9 m^3 of gas transportation capacity in total (Ma, 2017a, b), which will also benefit the construction of CO_2 pipelines or can even be directly utilized as CO_2 pipelines. Considering their hydrocarbon resources, I_1, I_2 and II_1 secondary tectonic units have high potential for CCS development.

Due to the relatively underdeveloped industry in western China, CO_2 emissions in most compressional basins are lower than in the eastern basins (Li et al., 2009; Wei et al., 2013), except for the Sichuan Basin where two of the most developed cities in China are located, Chongqing and Chengdu. The CO_2 emissions in the Sichuan Basin are mainly produced from cement manufacturing and power generation (Li et al., 2009). It is estimated that at least 0.39 Gt of utilizable CO_2 were emitted to the atmosphere in the Sichuan Basin in 2012, exceeding the sum of all other compressional basins in western China, and indicating the existence of sufficient CO_2 emissions in the Sichuan Basin to justify CCS development. Except for the northern part and southern edge of the Sichuan Basin, most regions have large CO_2 emission concentrations (Fig. 9d).

As the largest carbon emitter worldwide (Li and Huang, 2010), China accounts for 23.27% of global greenhouse emissions in 2012, whose emissions will peak around 2030 with between 14.7 and 14.0 $MtCO_2eq$ based on the current policy scenario and the Unconditional INDC scenario, respectively (Ma et al., 2014). CCS has been regarded as an essential technology for climate change mitigation in a series of released reports, e.g., the China's National Climate Change Programme, the China's Policies and Actions for Addressing Climate and the China's Intended Nationally Determined Contributions (Li and Huang, 2010; UNFCCC, 2015). At a smaller scale, the regions of Sichuan and Chongqing have proposed to explore and promote pilot and demonstration CCS projects within their Work Programme for "Control Greenhouse Gas Emissions During the Thirteenth Five-Year Plan", providing policy support for CCS development in the Sichuan Basin (Chongqing Municipal People's government, 2017; The People's Government of Sichuan Province, 2017). It is thus expected that the Sichuan Basin will draw the attention of different CCS stakeholders in the near future.

Based on the analysis of tectonic environments, hydrocarbon resources, CO_2 emissions and political support, the Central Gentle Fold Belt of the Sichuan Basin represents an optimal area to develop a CCS industry. Here, we present a preliminary discussion to identify the storage sites with greatest potential within this sector. From the Ediacaran (Sinian) to the Triassic, the Sichuan Basin was dominated by marine carbonate deposits with localized clastic sedimentation in stable sedimentary environments (Yang et al., 2016). Subsequently, after the marine-to-continental transition in the Late Triassic, the Sichuan Basin experienced continental sedimentation, mainly controlled by an alluvial fan-fluvial-delta-lacustrine depositional system. A series of source-reservoir-cap assemblages developed during the Ediacaran (Sinian), Cambrian, Silurian, Permian, Triassic and Jurassic (Luo et al., 2013; Wang et al., 2015), whose depths (generally more than 3500 m) meet the carbon storage requirements (Bachu, 2003; Wei et al., 2013). However, these reservoirs present two problems that should be taken into consideration. First, they tend to have low porosity and tight characteristics due to their deep burial with an average porosity of 3.24% and permeability of 1.45 mD for carbonate and 5.3% and 0.19 mD for clastic reservoirs (Wang, 2004; Yang et al., 2016). Second, caprocks deeper than around 2400 m cannot immobilize CO_2 permanently by structural trapping as efficiently as shallower reservoirs due to wettability reversal (Iglauer, 2018). Thus, it is priority to find shallower high-quality reservoir-caprock assemblages, which are mainly located in Jurassic and Triassic Xujiahe Formation (Fig. 10). In this sense, the Central Gentle Fold Belt contains the Guang'an, Hechuan and Bajiaochang large sized gas fields (around 300×10^9 m^3 of proved reserve in these gas fields (Ma et al., 2010)), whose reservoirs are dominated by Jurassic and Triassic Xujiahe Formation with reservoir and caprock burial generally ranging from 1500 m to 3500 m. Therefore, this area should be considered a priority for CCS implementation.

5. Conclusions

CCS will have an essential and challenging role in achieving the global target to limit the warming of global average temperature to 1.5 °C above pre-industrial levels. However, there is still a huge gap between the current CCS development and the ultimate objective, which is set to capture and store more than 300 Gt CO_2 by 2100 globally. CCS needs to develop fast, and for that purpose, it is crucial to consider the different potential storage options globally. Sedimentary basins in compressional tectonic settings are abundant and cover large areas on the Earth's surface. However, their potential for storing captured carbon has not been systematically evaluated against the geographic distribution of CO_2 emissions. To fill this knowledge gap, we employ a source-to-sink approach to evaluate the potential of compressional basins for CCS development based on basin distribution, hydrocarbon resources and CO_2 emissions. These inputs have been combined into an integrated evaluation parameter that allows the selection of five regions for potential CCS development in compressional basins: North America, north-western South America, south-eastern Europe, western Middle East, and western China. The most promising regions are located in the foreland basins of mountain chains, except in north-western South America, where the subduction of the Pacific and Caribbean plates under the South American plate resulted in the formation of hydrocarbon-rich retro-arc basins in Peru, Ecuador, Colombia and Venezuela. Among these potential regions, only North America and the Middle East currently have large-scale CCS facilities in operation, construction or development. The north-western South America and western Middle East regions present particularly high potential for CO_2-EOR and, in fact, there are two ongoing projects currently carrying out CO_2-EOR in the Middle East. Although CO_2-EOR is not a long-term solution for CO_2 emission reduction, because the overall emissions will increase due to the extra oil produced, it can initiate the development of a CCS industry in a suitable region while mitigating the upfront and operational costs with revenues from the enhanced production.

Being the largest coal user and CO_2 emitter in the world, China needs to decarbonise its energy and industrial sectors to promote a sustainable development. The most active and planned CCS facilities are located in the heavily industrialised east of the country, but our appraisal tool has identified the Sichuan Basin as a promising region for CCS development, according to the match between the existing carbon emissions and its potential storage capacity. The vast gas resources accumulated in the Sichuan Basin ensure the capacity and containment of the reservoirs. At the same time, the existing hydrocarbon infrastructure could be re-used

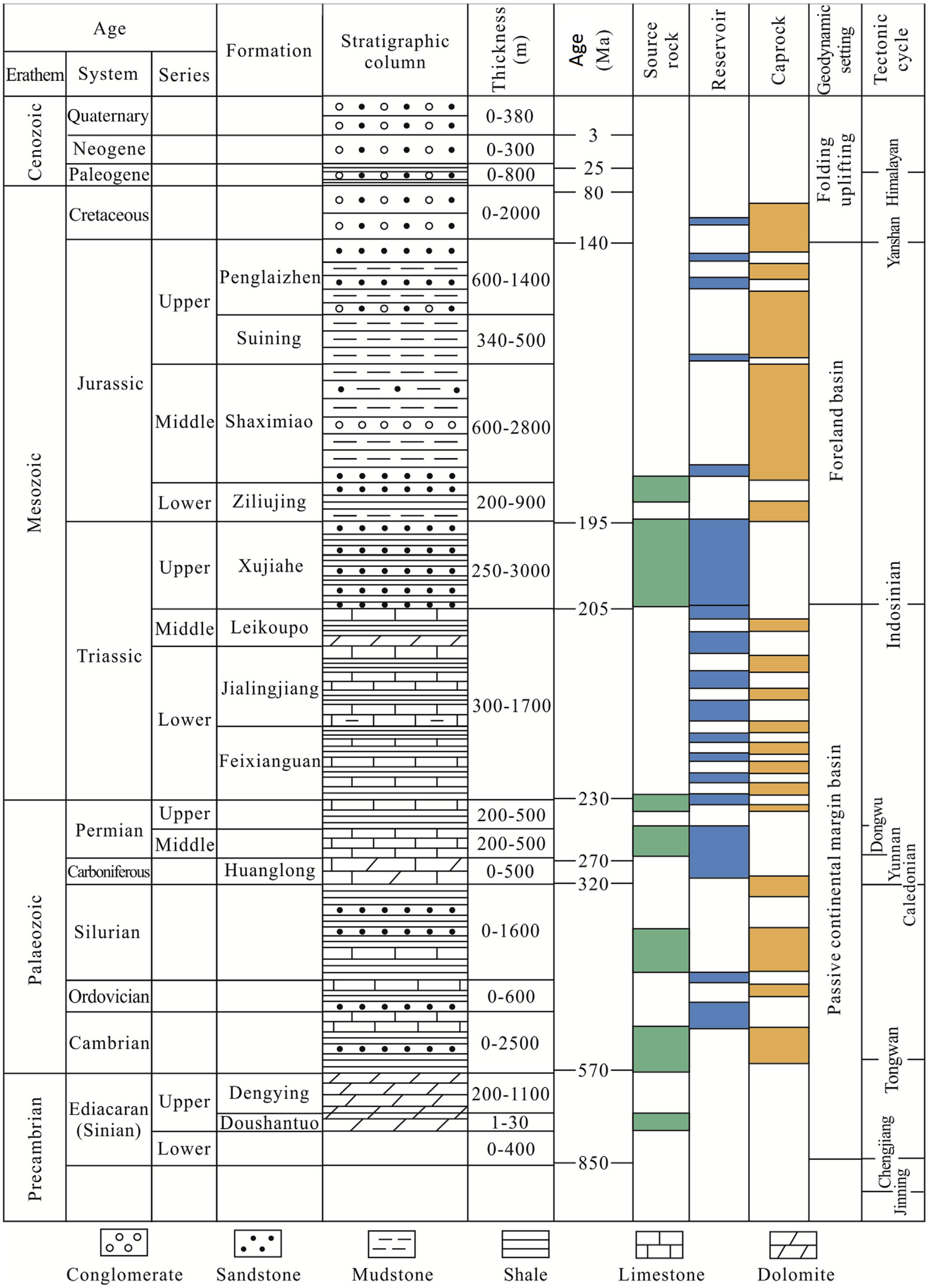

Fig. 10. Stratigraphic column, source-reservoir-caprock assemblages and tectonic evolution of the Sichuan Basin (after Luo et al., 2013).

for CCS, reducing the cost of implementation and hence increasing the prospects of this much needed industry in the region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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