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Potential of subsurface complex impact structures as sites for carbon sequestration

David T. King, Jr.*
Dept. of Geosciences, Auburn University, Auburn, Alabama 36849, USA
*Corresponding author: kingdat@auburn.edu

Abstract: The present paper examines the potential for at least some of the world's deeply buried complex impact structures, 4 to 25 km in diameter, as possible sites for carbon sequestration. The thesis presented here is that the complex impact structure's central uplift, which is a type of structural dome, could be a useful carbon-sequestration reservoir, if (1) the central uplift were overlain by relatively impermeable crater-filling deposits, including marine resurge deposits, and/or fine- grained post-impact sediments, and (2) if a thick sequence of overburden layers on the order of 2-3 km thick overlies the impact structure.

Keywords: Carbon sequestration, impact structure, reservoir.

Introduction

Subsurface injection of carbon dioxide (CO_2) has been shown to be a very important and highly promising method of sequestration or storage of large quantities of carbon that have been generated by industrial processes such as the production of electrical power by burning of fossil fuels (Metz et al., 2005; Bennaceur et al., 2008). Presently, targets for the sequestration of such carbon, i.e., in the form of supercritical liquid carbon dioxide, have been limited largely to sedimentary formations, specifically clastic rocks such as sandstones and carbonate rocks such as limestones and dolostones (Chopping and Kaszuba, 2017) that possess structural traps, such as structural domes or faults with associated fault traps. In order for subsurface injection of carbon dioxide (i.e., carbon sequestration) to be effective, there must a three stratigraphic components (Song and Zhang, 2019). From the top down, they are (1) a thick layer of overburden, (2) a cap-rock unit of essentially impermeable materials, and (3) a reservoir unit that serves as the host rock body receiving and storing the injection of supercritical liquid carbon dioxide. Within the reservoir unit, carbon dioxide is immediately retained and can be trapped long- term as a liquid and/or a gas within intergranular or other small open spaces. The carbon dioxide may reside for extended periods of time within the pore spaces, and these pore spaces containing the carbon-dioxide may be the sites of geochemical reactions between carbon dioxide and reservoir formation fluids and/or with constituent mineral components. These reactions can form new carbon-dioxide-bearing mineral cement thus creating a more permanent phase of carbon storage.

In a typical stratigraphic sequestration site, a host formation (or reservoir rock) has sufficient porosity and permeability either by its genetic nature or by post-lithification fracturing that it can readily receive substantial carbon-dioxide supercritical liquid injections. Further, the host formation is directly overlain by a low-permeability cap-rock unit (Lu et al., 2009; Michael et al., 2010; Griffith et al., 2011). This rock unit can be relatively thin as long as it is nearly impermeable or can be relatively thick and possess a low permeability. The cap rock must be able to resist (1) diffusive loss of dissolved gas through the cap rock, (2) leakage through the pore spaces after pressure has built up in the reservoir, and (3) leakage through any fractures over time (Song and Zhang, 2019). The overlying strata (or overburden) is typically relatively thick as compared to the cap-rock unit and even the reservoir unit. The overburden provides additional insurance that substantial leakage of carbon dioxide will not occur for a substantial period of time after injection. Therefore, several hundred meters or more of overburden is typically considered best for planning carbon-sequestration site development (Benson and Meyer, 2002; Vivaida et al., 2009).

Impact craters and impact structures

In the standard view of most terrestrial impact structures, there are two types – simple and complex (Melosh, 1989; French, 1998). Simple impact structures are about 1 to 4 km in diameter and have no central uplift, whereas complex impact structures are typically larger than 4 km and have a central uplift, which is a highly brecciated structural dome. Figure 1 shows an idealized sequence of events in the early formative history of a complex impact structure-forming event. In this sequence, it is evident how the central uplift forms during the impact event. The diameter sufficient for central uplift development is not well established and the distinction between simple and complex with regard to small impact structures can be somewhat arbitrary. However, all complex impact structures will have a central uplift feature. This central uplift may or may not, depending upon target and impact structure diameter, have an elevation that is above the level of the crater-filling breccia. Figure 2 shows an idealized cross-section of a complex impact structure where the top of the central uplift is approximately at the level of the lower part of the impact-crater filling unit (i.e., the crater-filling breccia). For reader's reference, a glossary of impact geology terms is included at the end of this paper. Impact craters differ from impact structures in that craters are well preserved but impact structures may be in any state of preservation; both may buried (Stöffler and Grieve, 2007). In this paper, the term impact structure is used instead of the crater because impact craters are more commonly simple in form, relatively young, and exposed at the surface. All three of these simple impact crater characteristics work against the typical simple impact crater being a good carbon-dioxide sequestration target, hence the emphasis on complex impact structures in this paper. In this paper, the term 'impact structure' will be used throughout.

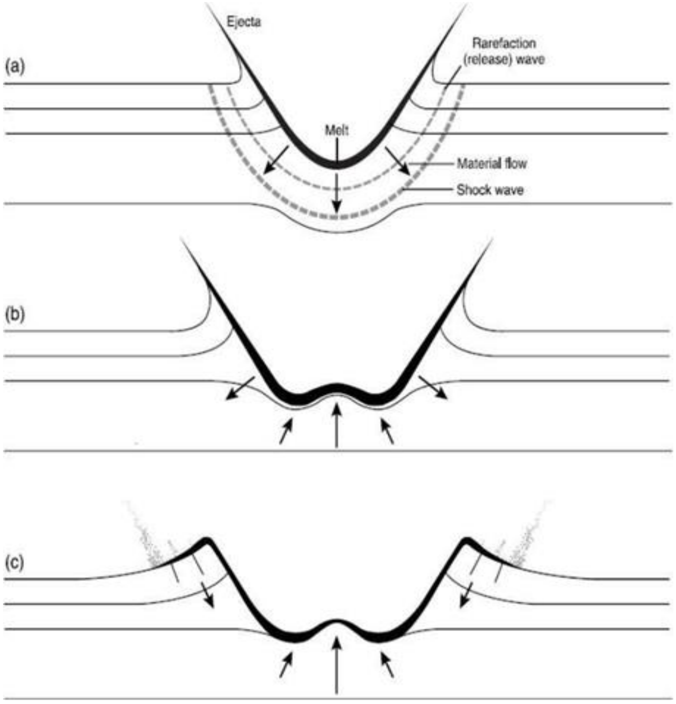

Fig. 1. Schematic sequential diagram showing the early stages in the development of a complex impact structure. (a) The impacting object has vaporized at the target is being deformed and the early, transient crater is starting to form by excavation processes. The shock wave front, rebounding release wavefront, the direction of material movement in the sub-crater area, potential melt zone, and early ejecta are labeled. (b) The forming crater begins to acquire a central uplift as the center rebounds while the surrounding part of the crater is still moving downward (see arrows). (c) The impact structure has formed and the faults of the rim are moving the sides downward forming a terraced rim while the inner part of the crater moves upward. Modified from French (1998). Used with permission of the Lunar and Planetary Institute.

In complex impact structures of substantial size, i.e., with diameters greater than 20 to 25 km, the central peak may collapse in its center, thus forming a peak ring structure (Melosh, 1989; French, 1998; Collins et al., 2008). Owing to the structural complexity of any given peak ring's internal features, it is suggested that complex impact structures of lesser size, which have a simpler central uplift feature (i.e., more like a structural dome), may be better targets for carbon sequestration operations. The peak ring can have an internal structure that is akin to a concentric anticline, but the peak ring can vary considerably from this generalized concept depending upon target material properties. In this paper, much larger impact structures (diameters greater than 100 km), including multi-ring basins such as Vredefort in South Africa and Sudbury in Canada, are not considered for carbon sequestration operations because of their scarcity and structural complexity. In complex impact structures, the amount of stratigraphic uplift (SU) of the central uplift area is about 0.1 of the impact structure's diameter (Grieve and Pilkington, 1996; French, 1998). The general mathematical relationship can be expressed as $SU = 0.1\ D$, and this has been established by the study of dozens of complex impact structures on

Earth (French, 1998). For an impact structure with a diameter equal to 20 km, i.e., an impact structure that would likely have a simple domal uplift at the center, the stratigraphic uplift is estimated to be 2 km. This does not mean that there is a central peak standing 2 km in height, but rather that target rocks or strata have been uplifted by 2 km. Shortly after impact, there is an episode of gravitational adjustment that typically reduces the height of the central uplift and lifts the surrounding crater floor or annular trough (Collins et al., 2008). The entire impact process occupies only a few seconds to a few tens of seconds during which the impact structure takes form and the target materials are energetically deformed. The extent of brecciation of target and the degree of preserved continuity of strata within the central uplift vary from one impact structure to another according to target lithology and stratigraphy, and other factors (Melosh, 1989; French, 1998).

For reasons to be discussed, it is suggested here that complex impact structures (i.e., those with a simple central uplifted area) that were developed in marine settings, or alternatively complex impact structures developed in terrestrial settings that become basins for long-term lacustrine sedimentation, may be the best target for carbon sequestration (i.e., the injection of supercritical liquid carbon dioxide). The next section explores this issue.

Complex impact structures as carbon sequestration targets

For a complex impact structure to properly function as a carbon-dioxide storage site, the impact structure likely must possess (1) a central uplift feature that will act as a structural trap, i.e., a relatively simple structural dome, (2) a relatively impermeable crater-filling unit, potentially including an upper fine-grained sediments, which may include marine resurge deposits, or alternatively a lacustrine sedimentation unit, and (3) a substantial overburden layer, including post-impact deposits and a sequence, strata of potentially great thickness and ideally relatively low permeability. Only impact structures with these three conditions are likely to be useful targets for carbon-sequestration drilling and injection, although a careful study of other impact structures may reveal individual exceptions.

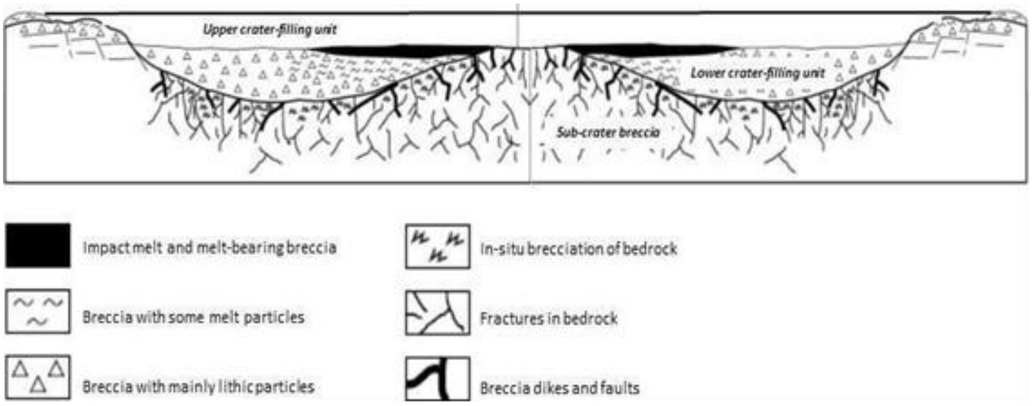

Fig. 2. Schematic diagram showing an idealized cross-section of a complex impact structure wherein the top of the central uplift is approximately at the level of the lower part of the impact crater-filling unit (i.e., the crater-filling breccia). The upper part of the impact crater-filling (sedimentary materials including marine resurge deposits or a lacustrine sediment layer) lies above the crater-filling breccia unit and reaches the level of the rim and its overlying ejecta deposit. A dark layer, which may be composed of melt materials (more common with terrestrial impacts versus marine), is shown at the top of the lower crater-filling unit. The sub-crater zone is highly brecciated and fractured and may contain some breccia dikes (see legend). The diagram is exaggerated in the vertical direction for clarity of features. Modified from French (1998). Used with permission of the Lunar and Planetary Institute.

For this scenario to work out favorably for carbon sequestration, the impact structure must be buried deeply enough that it has significant overburden, but not so deep that the cost of drilling injection wells is prohibitive, and not so deep that the impact structure is not well-explored and its characteristics reasonably well understood by previous drilling campaign(s) and/or seismic exploration. Also, the impact structure should be near enough to the source of carbon dioxide (and the industrial processing plant that liquefies this gas) so that it can be economically transported to the injection wells drilled into the impact structure.

Further, the impact structure's crater-filling unit must be able to function as a cap-rock unit, at least in part, which means that the impact structure most likely must be marine in origin or have had a history of lacustrine sedimentation. Marine impact structures typically possess thick crater-filling deposits of a fine-grained particulate nature, which are formed in part by processes associated with aqueous sedimentation and/or water-saturated mass movements and aqueous resurge deposition by returning sea-water flow. In the instance of a non-marine impact structure, it is possible that a thick deposit of lacustrine sediment within the impact structure's topographically lower interior area (i.e., an impact-formed lake). In either instance, a candidate complex impact structure would have to have been subsequently buried and thus be associated with a thick overburden layer as well.

Any complex impact structure will necessarily possess an extensive sub-crater breccia zone (Melosh, 1989; French, 1998; Collins et al., 2005). This breccia zone, known as the *parautochthonous breccia lens*, is the direct result of impact energy acting on target rocks and is typical of most impact structures, even those of marine origin. The parautochthonous breccia lens is developed by impact pressure and related shock waves that push target bedrock downward during the impact process. As with all impact structures, the nature of the target plays a very important role in the nature of the resulting impact deformation, and hence the composition and character of the sub-crater impact breccia lens is directly related to the target bedrock. This sub-crater breccia lens below the impact structure's crater floor (i.e., below its annular trough) is suggested as the main drilling target for the injection wells that will deliver supercritical liquid carbon dioxide. The laterally related central uplift (essentially a structural dome in the center of the impact structure's annular trough) would thus be the main reservoir zone to which the injected liquid will likely migrate owing to its buoyancy.

Figure 3 shows the formation of a complex impact structure in terms of pressure contours and flow lines of target materials. The 'displaced zone' will become the parautochthonous breccia lens. The 'excavated zone' will become ejecta, which will land mainly within a few crater radii of the impact structure. Some of this ejected material, which can have a substantial fine-grained component, will land upon the impact structure's rim, and will subsequently slump, slide, or flow back into the crater. And, some of the ejecta will fall directly back into the crater as well. These processes form the lower crater-filling breccia of many complex impact structures. Marine impact structures and other impact structures formed in water-saturated targets will develop also an upper, water-laid and/or water-saturated, crater-filling unit composed of displaced sedimentary target materials that slump, slide, or are washed back into the impact structure and thus lie on top of the lower crater-filling breccia. The washed-back material is a graded marine resurge deposit laid by returning seawater. An example of this two-part crater-filling stratigraphy as determined by a geophysical survey is shown in Figure 4.

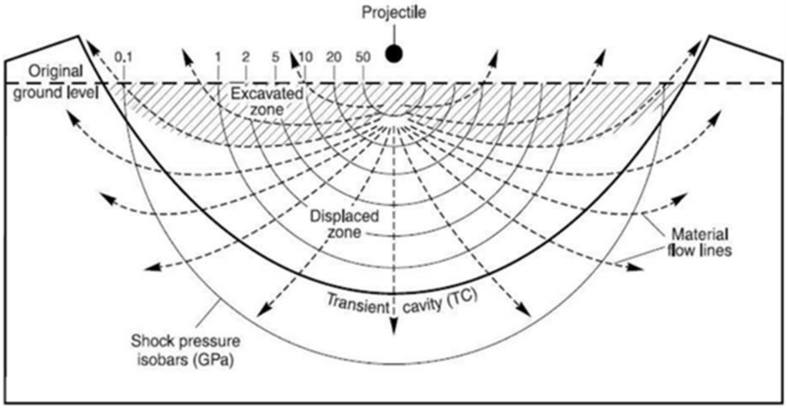

Fig. 3. Schematic diagram showing the formation of a complex impact structure with regard to pressure contours and flow lines of target materials. Specifically, the diagram shows the factors at work in the development of the *transient crater*, a short-lived impact feature that is rapidly modified by rebound and mass movement into the final impact structure's configuration. In the diagram, the 'displaced zone' will become the *parautochthonous breccia lens*, which is noted in the text. And, the 'excavated zone' will become ejecta, which will land mainly within a few crater radii of the impact structure. Dashed

arrows show the movement or flow of material in relation to the hemispherical isobars of pressure (in GPa). Modified from French (1998). Used with permission of the Lunar and Planetary Institute.

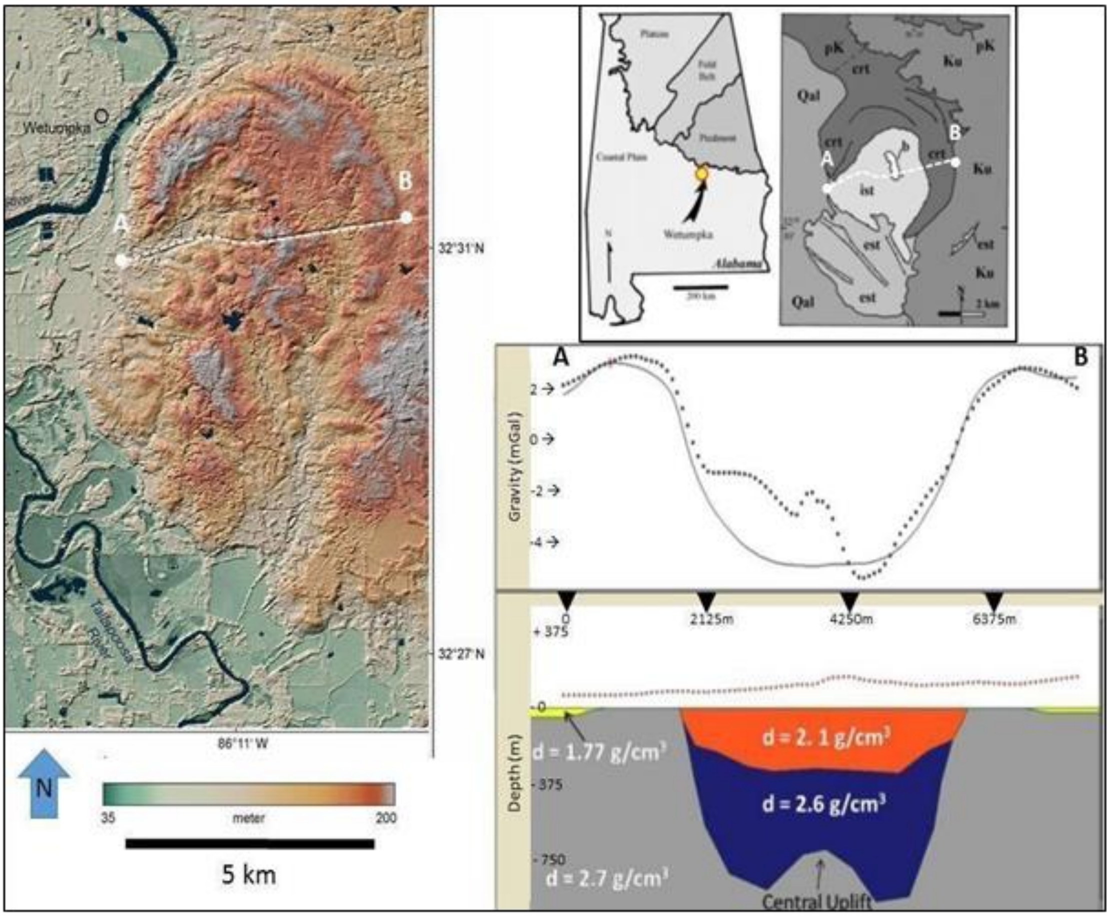

Fig. 4. Example of an impact structure with both upper and lower crater-filling units: Wetumpka impact structure, Alabama USA, a Late Cretaceous marine impact structure of ~ 5.5 km diameter. Wetumpka impact structures is shown in a hill shaded Sentinel-2 TanDEM-X DEM image (left), and on a location, map showing physiographic regions of the state of Alabama; a simple geological map of the impact structure is shown as well (inset maps on upper right). The location of the gravity transect, consisted of 105 points along a transect of approximately 6 km (from A to B on the maps). The gravity profile and related transect (lower right) reveals the two parts, upper and lower, of Wetumpka's impact-crater filling unit. They are distinguished on the basis of density: 2.6 g/cm^3 being the lower crater-filling breccia that formed by slump, slide, or flow back into the crater (with some ejecta falling back into the crater) and 2.1 g/cm^3 being the upper crater-filling unit that formed by water-saturated slump and slide and aqueous wash-back into the crater. Target bedrock (mainly schists and gneisses has a density of 2.77 g/cm^3 and Quaternary and Cretaceous unconsolidated sediments (yellow) have a density of 1.77 g/cm^3. Wetumpka impact structure is of the proper size for carbon sequestration, and has a relatively thick crater-filling unit (i.e., a cap rock), however, it is not deeply buried, and thus is not considered here to be a viable candidate impact structure for carbon-dioxide injection (i.e., there is no overburden layer). Digital elevation model from Manfred Gottwald (Gottwald et al., 2020; used with permission); inset maps and the gravity profile and cross-section are modified from Robbins et al. (2011); used with permission of the Lunar and Planetary Science Conference.

The boundary between the crater-filling unit and the underlying parautochthonous breccia lens is commonly a zone of intensively compressed rock and/or melted material. As such, this boundary or contact would form the base of the lower crater-filling (cap-rock) unit and would likely be the first relatively impermeable zone encountered by injected fluids that are migrating upward. Any injected carbon- dioxide liquid or gas that is not stopped or retarded at this boundary would be retained by or within the overlying crater-filling unit, especially by the upper, fine-grained sedimentary materials of the upper crater-filling unit. Figure 3 shows an idealized cross-section a complex impact structure. The lower zone of “fractured rock” is the parautochthonous breccia lens, and above this lies the upper and lower crater-filling deposits.

Figure 5, which is modified from Figure 2, is shown a possible carbon-dioxide sequestration scenario wherein injection wells (only one well is shown for simplicity) would place supercritical liquid carbon dioxide within the parautochthonous breccia lens below the annular trough of the impact structure. As the injected fluid moves upward, owing to it buoyancy, it would tend to move along the base of the crater-filling unit and then accumulate within the adjacent central uplift area, which acts as a dome-shaped structural trap.

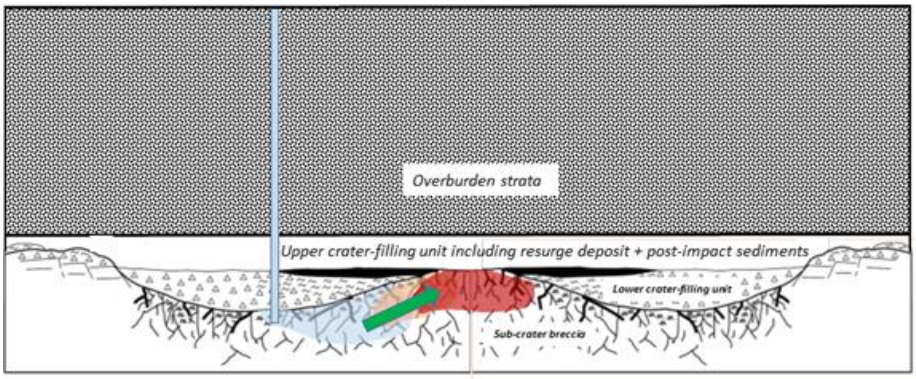

Fig. 5. Schematic diagram, modified from Figure 2, showing an idealized cross-section of a complex impact structure that has been drilled for carbon-dioxide sequestration and the single (example) injection well (not to scale) is placing supercritical liquid carbon dioxide within the impact structure’s sub-crater (parautochthonous) breccia lens. This buoyant fluid would tend to move upward, where it is constrained by the cap-rock (crater-filling) unit, and thus move upward toward the adjacent central uplift area (as indicated by the green arrow), which acts as a dome-shaped structural trap. The initial injection plume is light blue, and with time, the fluid moves to the areas shaded light brown and then ideally to the light red area at the apex of the central uplift. The plume movement is modeled after a diagram in Hefny et al. (2020). The diagram is exaggerated in the vertical direction for clarity of features. Figure
2 was modified from French (1998); used with permission of the Lunar and Planetary Institute.

Buried complex impact structures of the proper size across the world

According to the internationally recognized Earth Impact Database (Refer: http://passc.net/EarthImpactDatabase/New%20website_05-2018/Index.html) which tracks the exploration and identification of impact structures worldwide, there are about 200 known impact structures in the world, of which 61 are in North America. Of these 61, fourteen are (1) in the size range of 4 to 25 km (what is thought to be the minimum size of a complex impact structure and the maximum size of a complex impact structure that has a simple central uplift feature, i.e., not a peak ring, respectively), and (2) are buried (i.e., “not exposed” according to the Earth Impact Database’s North American table). Table 1 lists these North American complex impact structures, but the scope of this paper does not include a review of each one of the 14 impact structures listed and their suitability for carbon sequestration (including depth of burial) is not determined here. The point of Table 1 is to show that there are a significant number of such impact structures that could be investigated for carbon sequestration in North America alone. Similarly, in Europe, there are fourteen complex impact structures in the size range of 4 to 25 km in diameter among the 41 known impact structures in Europe according to the Earth Impact Database. Of course, there are other potentially useful complex impact structures in other parts of the world as well, but North America and Europe, by far, have the most listed in the Earth Impact Database. Further, there are other likely complex impact structures that have not been proven but may very well be of impact origin. These are commonly referred to a ‘potential impact structures.’ These may be equally useful for carbon sequestration in the future once they are better explored and understood. The total number of these may be substantially more than the total number of known impact craters as of today.

Table 1. North American complex impact structures that are buried and have diameters in the range of 4 to 25 km, as noted in the text. From the Earth Impact Database's table for North America.

Name	Location	Diameter (km)
Ames	Oklahoma	16
Avak	Alaska	12
Calvin	Michigan	8.5
Cloud Creek	Wyoming	7
Deep Bay	Saskatchewan	13
Des Plaines	Illinois	8
Eagle Butte	Alberta	10
Elbow	Saskatchewan	8
Maple Creek	Saskatchewan	6
Marquez	Texas	13
Nicholson	Northwest Territories	13
Red Wing	North Dakota	9
Steen River	Alberta	25
Wanapitei	Ontario	8

Two examples of relatively well-known and deeply buried complex impact structures from Table 1 are Ames (a 16 km structure in Oklahoma) and Red Wing (a 9 km structure in North Dakota). Both of these structures are buried by more than 2 km of overburden and have been extensively drilled and studied by seismic and other geophysical methods. Both of these complex impact structures are in hydrocarbon-producing areas, and they both have produced hydrocarbons as well (Donofrio, 1998; Barton et al., 2010). Being in a hydrocarbon-producing area was a large factor in their discovery and exploration, but is not viewed as a requirement for carbon-sequestration activity according to this paper. It should be noted that carbon sequestration activity within more traditional structural traps that occur within current and former oil fields has been undertaken in the past. The carbon-dioxide injection can be used as a driving mechanism for enhanced oil recovery, given the proper setting (Song and Zhang, 2019). In this paper, the hydrocarbon-producing aspect of these two examples is not considered with regard to carbon sequestration.

North American examples of deeply buried complex impact structures

At Ames impact structure, the target was an Ordovician shallow marine shelf area adjacent to a deeper water region that was located south of Oklahoma at the time of impact. Because Ames impact structure is of marine origin, it has a substantial, relatively fine-grained crater-filling unit (i.e., the lower shaley facies of the McLish Formation) that likely includes resurge deposits. Overburden strata are of marine and non-marine origin and total over 3 km in thickness (Johnson and Campbell, 1997; Barton et al., 2010). The main characteristics of deep burial, marine origin with a relatively impermeable crater-filling unit, and a central uplift area, make Ames impact structure a good model for carbon sequestration study. It is not suggested here that Ames could or should be used for this purpose, only that further study of this structure as a model could prove useful to better understanding the potential for carbon sequestration in such an impact structure.

At the Red Wing impact structure, the target was a Late Triassic to Early Jurassic shallow marine shelf area attendant to the western inland sea area of North Dakota, which existed in the target area at the time of impact. Because the Red Wing impact structure is of marine origin, it has a substantial, relatively fine-grained crater-filling unit that likely includes resurge deposits. Overburden strata are of marine and non-marine origin and total over 2 km in thickness (Koeberl et al., 1996; Barton et al. 2010). As with Ames in Oklahoma, the main characteristics of deep burial, marine origin with a relatively impermeable crater-filling unit (i.e., the shaley Bowes Member of the Piper Formation), and a brecciated central uplifted area, make Red Wing impact structure a good model for carbon sequestration study. As with Ames, it is not suggested here that Red Wing could or should be used for this purpose, only that further study of this structure as a model could prove useful to better understanding the potential for carbon sequestration in such an impact structure. Figure 6 shows an idealized complex impact structure in cross section that has a lower crater - filling breccia (black area) and an upper crater-filling unit of fine-grained materials. This complex impact structure is also deeply buried (note that the overburden shown in not to scale). This generic cross-section would apply to both Ames and Red Wing impact structures discussed briefly above as well as other potential deeply buried, complex impact structures of the size range discussed earlier.

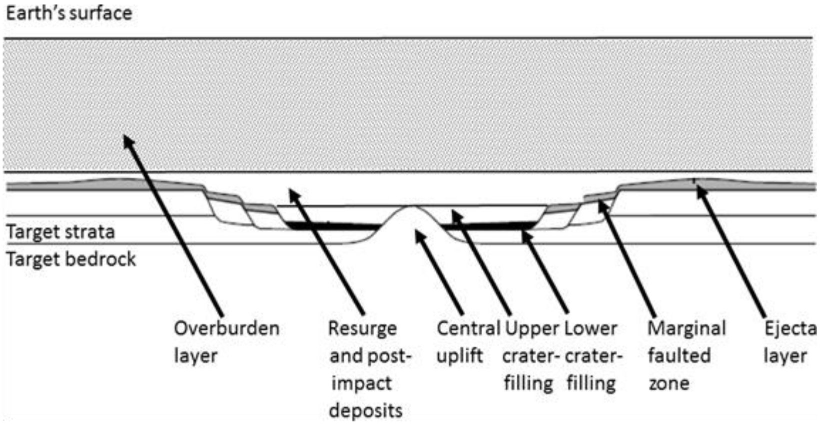

Fig. 6. Schematic diagram showing an idealized complex impact structure with a simple central uplift feature, which is similar to many small (4 to 25 km), marine, complex impact structures including Ames and Red Wing. This impact structure has a lower crater-filling breccia (black zone) and an upper crater-filling unit of fine-grained materials. The overlying 'resurge and post-impact deposits' is a layer that consists of resurge materials from returning seawater flow (actually part of the upper crater-filling unit), which are in continuous depositional contact with overlying post-impact deposits (actually part of the overburden unit). This combined resurge and post-impact deposit is akin to the lower shaley facies of the McLish Formation at Ames impact structure (Oklahoma) and the shaley Bowes Member of the Piper Formation at Red Wing impact structure (North Dakota). This idealized complex impact structure is deeply buried; the overburden shown is not to scale. Modified from French (1998); used with permission of the Lunar and Planetary Institute.

Conclusions

This paper introduces the concept of carbon sequestration within a particular type of impact structure, namely impact structures that are deeply buried (i.e., they have a significant thickness of overburden materials on top of them) and have a relatively impermeable crater-filling unit that consists largely or entirely of fine-grained sediments (e.g., sedimentation that is expected in a marine impact scenario or lacustrine crater deposition). Complex impact structures, likely between 4 and 25 km in diameter, will typically possess simple central uplifts that form a type of relatively simple structural dome that is commonly characterized by highly fractured and brecciated rocks. These central uplifts could be the structural dome that holds carbon dioxide or the purposes of subsurface sequestration.

The simple idea of this paper is that supercritical liquid carbon dioxide, the typical carbon storage phase, could be injected into complex impact structures, specifically within the sub-crater breccia zone, at sites that are adjacent to the central uplift and thus allow the injected buoyant fluid to move from the well bore upward into open space within the sub-crater breccia zone and then on to the domal central uplift feature. The carbon dioxide should rise though the crater breccia and come to reside mainly in the central uplift itself. The injected carbon dioxide would then reside long-term in the pore spaces of the brecciated rock or react with the host rock to form new cements. The degree of success of this suggested process depends upon the characteristics of the individual impact structure and to some extent its physical location with respect to the carbon source and the facilities that produce supercritical fluids. Therefore, careful study of any complex impact structure to be considered for carbon sequestration is strongly indicated. There are several known deeply buried complex impact structures in North America, and similarly in Europe, and there are several other known and suspected deeply buried complex impact structures around in the world. Most of these complex impact structures have known characteristics that generally suggest they deserve further study for possible carbon sequestration. There are many other similar complex impact structures around the world that are not deeply buried, but afford opportunities for surface or shallow subsurface study of their physical characteristics that would afford us insights into the more deeply buried impact structures. It is hoped that this paper will stimulate interest in exploring complex impact structures with the idea in mind of potentially using them for carbon sequestration in the future.

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Glossary

Definitions of key terms used in this paper. These definitions are similar to those found in Stöffler and Grieve (2007) but have been modified by the author for this paper.

TERM	DEFINITION
Annular trough	A complex impact structure's topographically depressed, annular feature surrounding the central uplift where the crater-filling unit largely resides.
Central uplift	A geological feature, much like a structural dome that is highly brecciated and deformed, which exists in the center of a complex impact structure and is the result of rebound (uplift) in the impact deformation process. See also stratigraphic uplift.
Complex impact structure	Geological structure caused by the hypervelocity impact of a meteorite, asteroid, or comet, regardless of its state of preservation of depth of burial, and having sufficient size (generally more than 4 km and up to 100 km in diameter) that a central uplift feature is developed during impact.
Crater moat	See annular trough.
Crater rim	In complex impact structures, the crater rim is a slightly elevated annular area encircling the interior depressed area and central peak, and consisting of down-faulted (and thus terraced) terrain, which receives substantial ejecta deposits. May be overlain by some resurge deposits and/or post-impact sediments.
Crater-filling unit	Deposit of fragmental and melted material that has fallen back into the impact structure or has slumped, flowed, or washed back into the lower reaches of the impact structure (if marine in origin). May consists of an upper and lower part, and may include marine resurge deposits. In the instance of a dry terrestrial impact, subsequent lake deposits (lacustrine sediments) may comprise the upper part of the crater-filling unit.
Ejecta	Fine to extremely coarse material that consists of broken rock and minerals and (in some instances) melted target rock materials, which has been launched from impact structure during the excavation phase of the impact process.
Impact crater	Generally circular feature of a planet's surface that was formed by the hypervelocity impact of a meteorite, asteroid, or comet.
Impact structure	Geological structure caused by the hypervelocity impact of a meteorite, asteroid, or comet regardless of its state of preservation of depth of burial.
Overburden	Sedimentary deposits that overlie buried impact structures and represent sedimentation for a sustained period (usually many millions of years) after the impact event has ended. The overburden sequence of deposits may begin with the onset of post-impact sedimentation.
Parautochthonous breccia lens	A sub-crater breccia zone that forms as the result of the downward movement of impact energy into the underlying target bedrock. May include dikes filled with breccia and/or impact- melted rock.
Peak-ring	A structural feature that forms as the result of the central collapse of a central uplift; generally this occurs in complex impact structures of more than 25 km in diameter (up to about 100 km in diameter).
Post-impact sediments	In marine impacts, these are generally fine-grained sediments that were being deposited on the sea floor prior to impact, and their deposition resumed after the impact event ended (i.e., after deposition of resurge sediments ended). May directly overlie resurge deposits and/or the upper crater-filling unit. Post-impact sediments, where present, are the basal deposits of a buried impact structure's overburden.
Resurge deposits	Deposit of fragmental and melted material that has washed back into the impact structure as a result of the rapid return of displaced seawater in a marine impact event. Resurge deposits generally contain a large proportion of fine materials and are size graded.
Simple impact structure	A bowl shaped impact structure that has no central uplift but may have a crater-filling unit
Stratigraphic uplift	A measure of the extent to which rock material has been brought upward during the formation of the central uplift of a complex impact structure. Generally, rocks are brought upward about a factor of 0.1 of the impact structure's rim diameter. Thus, a 10 km diameter impact structure will likely have rocks from 1 km depth within the central uplift.
Transient crater	The impact crater that forms early during the impact process; usually much deeper than the final crater or impact structure. The transient crater ends when rebound of the target materials begins to lift the annular moat and central uplift as the final crater takes form.

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