**Sr isotopic compositions of the interstitial water and carbonate
from two basins in the Gulf of Mexico: Implications for fluid
flow and origin**

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Abstract

Strontium isotopic compositions of the interstitial water and carbonate from marine sediments
sampled during IODP 308, in two basins (the normally-pressured Brazos-Trinity Basin IV and the
over-pressured Ursa Basin) on the northern slope of the Gulf of Mexico, are present in this study. In the

Brazos-Trinity Basin IV, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the interstitial water range from 0.70917 to 0.70954, with carbonates sharing similar or slightly lower values from 0.70851 to 0.70952. The interstitial water above 31 m shows similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratio close to that of seawater, whereas the interstitial water below 31 m shows more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, possibly indicating a water/rock interaction between the fluid and silicate component in the deep basin sediments. The Sr-isotope ratios of the carbonates are less radiogenic than the seawater, which may reflect a terrestrial carbonate input (such as limestone) transported through the Brazos and Trinity rivers. In the Ursa Basin, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the interstitial water range from 0.70887 to 0.70999, those of the carbonate vary from 0.70808 to 0.70930. Both the interstitial water and carbonate show a similar trend of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios throughout the depth. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the interstitial water decrease from the sea floor surface to the minimum at the Seismic Reflector S10. A lateral fluid incursion with less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios along the Seismic Reflector S10 can be inferred in the Ursa Basin. It is suggested that the lateral fluid incursion shows a seawater origin, modified by diagenetic reactions including the dissolution of halite. Between the Seismic Reflector S10 and S40, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the interstitial water increase linearly to the maximum. Along the Seismic Reflector S40, a lateral fluid incursion with more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios is again recognized. The fluid may have also originated from seawater, but modified by the diagenesis of terrigenous sediments, likewise characterized by highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ compositions. A two-dimension fluid-flow model in the Ursa Basin is established.

Keywords: Sr isotopes; interstitial water; carbonate; fluid flow; IODP308; Gulf of Mexico

1. Introduction

Rapid sedimentation creates overpressure and controls compaction-driven fluid flow ([Bredehoeft](#)

and Hanshaw, 1968; Bethke, 1986; Harrison and Summa, 1991; Judd and Hovland, 2007; Sun et al., 2012; Sun et al., 2014). Near seafloor fluid flow are important to understand because they influence stability of the slope (Flemings et al., 2006). Fluid-flow model can be constructed through fluid pressure (Flemings et al., 2008). The lateral fluid driven by the topography can be recognized through the detection of either pressure measurement or geochemical data (Flemings et al., 2006; Li and Jiang, 2010).

The chemical compositions of pore fluids and sediments can provide valuable information on the fluid sources, fluid pathway, diagenetic reactions and the burial history of the sediments (Teichert et al., 2005; Reitz et al., 2007; Jiang et al., 2015; Ye et al., 2015). For example, strontium isotope is a key tracer for fluid/rock reactions (Stueber et al., 1984; Teichert et al., 2005), fluid pathway (Teichert et al., 2005), fluid mixing patterns and sources (Reitz et al., 2007; Sun et al., 2011). The Integrated Ocean Drilling Program (IODP) undertook Expedition 308, dedicated to the study of over-pressure and fluid flow on the continental slope of the Gulf of Mexico. Drilling at the normally-pressured Brazos-Trinity Basin IV and the over-pressured Ursa Basin (Fig.1), was revealed an active hydrodynamic environment that provided an insight into the geological processes near the sub-seafloor. A two-dimension fluid flow model in the Ursa Basin was established (Flemings et al., 2006, 2008; Binh et al., 2009; Stigall and Dugan, 2010). This model focused mainly upon the over-pressure driving the fluid flow in the Blue Unit (shown in Fig.1c) at the bottom of the basin. The model characterizes upward flow above 200 m and downward flow below 200 m at Site U1324, but the source of upward and downward flow is puzzled.

In addition, a lateral fluid along the Seismic Reflector S10 at shallower depths was also recognized (Flemings et al., 2006; Li and Jiang, 2010), however the source of this lateral fluid

incursion is still unknown. In this study, Sr isotopic compositions of the interstitial water and carbonate from sediments recovered in the normally-pressured Brazos-Trinity Basin IV and the over-pressured Ursa Basin in the Gulf of Mexico during IODP308 drilling are reported and compared. Attempts are made to demonstrate Sr isotope behaviors as an indication of fluid sources and pathway in the two basins studied and the burial history of the sediments.

2. Geological settings

2.1 Brazos-Trinity Basin IV

Brazos-Trinity Basin IV is located ~250 km south-southeast of Houston, Texas (USA) in a water depth of ~1400 m (Fig.1). It was formed during the step-wise sea level fall between 115 and 15 ka, ending just prior to the meltwater pulse to the Gulf of Mexico at 14 ka (Mallarino et al., 2006). The basin is one of a chain of 5 basins that are separated by inter-basinal highs on the slope of the Gulf of Mexico (Winker, 1996; Flemings et al., 2006). These basins have been fed directly by sediments delivered to the shelf edge by the ancestral Brazos and Trinity rivers and associated deltas. The basins are connected by a southerly-trending system of slope channels. The Brazos-Trinity Basin IV is only filled partially with an onlap-fill sequence, representing the ultimate terminus for the surface channel complex (Winker, 1996). Because of a relatively low sedimentary rate, the Brazos-Trinity Basin IV is deemed as a classic area for the analysis of turbidite depositional environments, and has been used as a modern analogue to describe the formation of deepwater turbidite deposits.

During IODP308 the Brazos-Trinity Basin IV was drilled and sampled, to establish a reference section to determine the change in rock and fluid properties at the normally-pressured basin location. Site U1319 is located in 1430 m of water depth on the southern flank of the Brazos-Trinity Basin IV

(Fig.1b). Here sedimentary section is condensed and influenced only minimally by turbidite influx into the basin. One 156 m thickness of sediment was obtained and divided into six lithostratigraphic units. This was based upon visual observation, analysis of smear slides and on spectrophotometric data (Flemings et al., 2006). Lithostratigraphic Unit I (0 to 3.33 m) is enriched in visible planktonic foraminifers, lacks any turbidite beds of laminae, being interpreted as a Holocene drape. Subunit IIA (3.33 to 6.2 m) is dominated by quartz with minor amounts of carbonate. Graded sand and silt laminae are indicative of turbidite influx during deposition. Subunit IIB (6.2 to 12.0 m) is composed mostly of homogeneous black, organic-rich clay, considered to be the result of a mass transport deposit. Subunit IIC (12.0 to 14.0 m) consists of green clay with silt and fine sand laminae including rare shell fragments and mud clasts. This is interpreted as being the result of turbidity current deposition. Subunit IID (14.0 to 17.25 m) is clay, without visible macroscopical foraminifers, which lacks evidence of turbidite deposition and is transitional to Unit III. Lithostratigraphic Unit III (17.25 to 23.5 m) consists of clay with macroscopically visible foraminifers (the percentage of foraminifer <5%). This lacks turbidite features suggesting a period of hemipelagic sedimentation. A distinct 2 cm thick ash layer occurs at 22.73 m. Lithostratigraphic Unit IV (23.5 to 29.5 m) is composed dominantly of clay with very fine sand laminae. It records another pulse of turbidite input to the basin. Lithostratigraphic Unit V (29.5 to 31.0 m) contains foraminifer- and nannofossil-bearing clay, recording a period of minimum siliclastic input to the basin and hemipelagic-dominated sedimentation. Finally, Lithostratigraphic Unit VI (31.0 to 155.8 m) contains rare foraminifers and lacks any obvious evidence of a sandy turbiditic input, suggesting deposition from muddy plumes or from a nepheloid layer. It is the pre-fan of the Brazos-Trinity Basin IV.

2.2 Ursa Basin

The Ursa Basin is located on the northeastern Gulf of Mexico continental slope in water depth of 800 to 1400 m. It is located 210 km due south-southeast of New Orleans, Louisiana (Fig.1a). The Ursa Basin resulted from the interplay between sedimentation and erosion during the late Pleistocene, beginning about 70 ka. McFarlan and LeRoy (1988) considered it as the center of deposition for late Pleistocene sediments supplied from the Mississippi River.

The strata of Ursa Basin have received considerable scientific attention since the 1990's when over-pressured and unconsolidated sands in the shallow section plagued drilling operations (Eaton, 1999). Sawyer et al. (2007) presented a comprehensive analysis of the depositional system. In this basin, sediments have been divided into three successive (from base to top) depositional units: the Blue Unit, the Ursa and Southwest Pass Canyon channel-levee systems, and the distal turbidite and hemipelagic deposits (Fig. 1c). The Blue Unit has been interpreted as being deposited by turbidity currents during marine isotope stages (MIS) 2-4 (Winker and Booth, 2000). At this time the sea level fall led to rapid deposition of thick sand and mud sequences (Coleman and Roberts, 1988). The unit forms a regional permeable unit, composed of interbedded thick sandstone and mudstone (Fleming et al., 2006). The Blue Unit is overlain by a thick sequence composed of a succession of channel-levee systems, the Pass Canyon and the Ursa Canyon, which have been eroded intensively and have incised the underlying Blue Unit (Pulham, 1993). Site U1322 and U1324 were drilled in the Ursa Basin (Fig.1b). On average, the sedimentation rate across the entire interval is ~2.5 times greater at Site U1324 than at Site U1322 (10 mm/y versus 4 mm/y). Low-permeability mudstones cap the channel-levee systems and are thicker to the west (Site U1324) than to the east (Site U1322). Multiple MTDs are present throughout section, especially in the vicinity of Site U1322.

3. Samples and analytical methods

Whole round sediment cores, each 5 cm in length, were sliced and squeezed using stainless steel squeezers immediately after core retrieval on the deck of the JOIDES RESOLUTION during the IODP308 Expedition. The squeezed sediments were dried and retained in bottles for the analysis of solid phase for shore-based isotopic analysis. The interstitial waters were filtered using a 0.45 μm membrane filter. The main chemical parameters and the ion concentrations of the interstitial waters were determined on the shipboard (as described in [Flemings et al., 2006](#)). The determination of Sr isotopic compositions of the interstitial waters and carbonates from the sediments was carried out by thermal ionization mass spectrometry (Finnigan Triton TI) at the Department of Earth Sciences of Nanjing University.

The sediment sample powder (50 mg) was reacted with 2 mL of 1 mol/L acetic acid for 15 minutes in an ultrasonic bath. It was centrifuged, extracting the supernatant in the case of the carbonate fractions. The procedure was repeated three times, after which the supernatants were dried for the Sr isotopic analysis of the carbonate fractions.

Approximately 0.1 mL of interstitial water sample was taken in a Teflon vial, then placed upon a hot plate to dryness. All the samples were re-dissolved in 1 mL of double distilled 4 M HCl, centrifuged and the supernatants were loaded directly on cation exchange columns (AG 50W-X8, 200-400 mesh). 2 mL columns and 2.5 M HCl as eluents were used. The Sr fraction was collected in about 7 mL 4 M HCl and dried down. Following column separation, the samples were taken up in 1 μL 1 M HCl and 1 μL TaF₅ solution and loaded onto degassed W filaments. Ion beams of 2 to 5 V of ⁸⁸Sr were obtained during mass spectrometer measurements. The precision resulted in absolute uncertainties in the ⁸⁷Sr/⁸⁶Sr ratio is about 2×10^{-5} . Measurement of ⁸⁷Sr/⁸⁶Sr ratio for NIST 987 Sr standard during the

course of these analyses yielded a value of 0.710247 ± 0.000015 (2σ , $n = 10$), which is the same as the reported value by other laboratories (e.g., 0.710254 ± 0.000023 , [McArthur, 1994](#)).

4. Results

Chemical and isotopic data measured in this study are listed in [Tables 1, 2](#) and shown in [Figure 2](#).

4.1 Brazos-Trinity Basin IV

The distribution patterns of Sr isotopic compositions of the interstitial water and carbonate samples are presented in [Fig.2](#). The interstitial water shows a $^{87}\text{Sr}/^{86}\text{Sr}$ range from 0.70917 to 0.70954 ([Table 1](#)). Above 31 m, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios show a limited variation from 0.70918 to 0.70920, which are identical to the Pleistocene seawater ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70919$, [Hodell et al., 1990](#)). Below 31 m, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of interstitial water increase from 0.70921 at 31m to 0.70954 at the bottom of the core. These values are more radiogenic than the shallower interstitial water. The range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of carbonate is from 0.70851 to 0.70952. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the carbonate recorded the original Sr isotopic compositions of the water in which they precipitated ([Hess et al., 1986](#); [McArthur et al., 2001](#)). Thus, strontium isotopes can be used to constrain the source of fluids for authigenic carbonate precipitation in marine sediments. However, at Site U1319, carbonate Sr values are distinguishable clearly from the pore water and contemporaneous seawater.

4.2 Ursa Basin

The variations in Sr isotopic composition of the interstitial water and carbonate samples with depth at Site U1322 are shown in [Fig. 2](#). The interstitial water shows a $^{87}\text{Sr}/^{86}\text{Sr}$ range from 0.70887 to 0.70971 ([Table 2](#)). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the carbonate vary from 0.70808 to 0.70930. Regardless of the extra low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio at 8.5 m, the trend in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios varying with depth in the

interstitial waters is similar to that of carbonate. Nonetheless the $^{87}\text{Sr}/^{86}\text{Sr}$ in the carbonate is less radiogenic than in the interstitial water. Around Seismic Reflector S10, less radiogenic Sr isotopic composition is observed both in the interstitial water and carbonate. The variation in Sr isotopic composition of interstitial water at Site U1324 is shown in Fig.2. Similar to Site U1322, minimum and maximum $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are observed around the Seismic Reflector S10 and S40, respectively.

5. Discussion

5.1 The characterization of Sr isotopic composition of interstitial water and carbonate in the normally-pressured Brazos-Trinity Basin IV

The variation in Sr isotopic compositions of the interstitial water at Site U1319 can be divided into two parts at a depth of 31 m. Above 31 m, the ratio of $^{87}\text{Sr}/^{86}\text{Sr}$ centers around 0.70919, which lies close to that of Pleistocene seawater. The sedimentary section above 31 m represents the basin fill succession, the homological Sr isotopic composition of the interstitial water shows the primary Sr-isotopic compositions of seawater. Below 31 m, the pre-fan of the basin, ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr concentrations increase linearly with core depth. There is a broad trend on a plot of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio versus $1/\text{Sr}$ (Fig.3), representing mixing between seawater and an end-member fluid with more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ (about 0.7106). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the detrital silicate component of the sediments between 31 m and 133 m have been analyzed with a variation from 0.7276 to 0.7363. The presence of a highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ component in interstitial water indicates interaction with the silicate components in the deep basin.

The variation of carbonate content in the sediment against depth at Site U1319 is shown in Fig. 4. The carbonate content is relatively high in the uppermost sediments (Unit I). It then decreases rapidly,

and remains constant in the lower part until the depth of SMI (~14 m Unit IIA-IIC, [Flemings et al., 2006](#)). Increased carbonate content keeps constant in the Lithostratigraphic Unit III. The maximums of Sr/Ca and Mg/Ca ([Fig.4](#)) between 14 m and 24 m indicate the occurrence of high-Mg calcite precipitates from the interstitial water. The maximum carbonate content occurs at around 24 m.

Comparing the strontium isotopic compositions between the interstitial water and carbonate, at depths of 14-24 m and 93 m where they are consistent, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is less radiogenic in the carbonate than in the interstitial water. Between 14 m and 24 m, the carbonate may have precipitated from the interstitial water, recording the $^{87}\text{Sr}/^{86}\text{Sr}$ signal of the interstitial water. Thus the carbonate has a similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratio to that of the interstitial water. Apart from the depth of 14-24 m, the ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ show mostly less radiogenic in the carbonate. The dissolution of carbonate rocks (e.g., calcite, dolomite) and evaporitic sulphates (e.g., gypsum, anhydrite) is considered elsewhere to be the major source of Sr to the oceans ([Brass, 1976](#)). The Sr isotopic signature of the weathering of a terrestrial carbonate source today ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7077$, [Palmer and Edmond, 1989](#)) is similar to that of average Phanerozoic seawater (~ 0.708 , [Veizer and Mackenzie, 2003](#)). The Brazos-Trinity basins have been fed directly from sediments delivered to the shelf edge by the ancestral Brazos and Trinity rivers and associated deltas. The Brazos and Trinity rivers traverse Texas. The Brazos River flows through Cretaceous shale, chalk and marl, Tertiary shale and sandstone, Pliocene, Pleistocene, and Holocene sand and mud. The Trinity River flows through Miocene, Pleistocene, Holocene sand and clay. [Christian et al \(2011\)](#) reported both the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70742 to 0.70804, average 0.7076) of Cretaceous marine limestone bedrock and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.70778 to 0.70918) of dissolved Sr in stream water in Austin near the valley of the Brazos River. The range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of carbonate is from 0.70851 to 0.70952 at Site U1319, which is mostly less radiogenic than that of the modern

seawater. Here the lowest ratio ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70851$) indicates that the carbonate of the sediment at Site U1319 may originate partly from the terrestrial source.

In the normally-pressured Brazos-Trinity IV Basin, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of interstitial water and carbonate have the following characteristics: (i) in the shallower interstitial water, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are close to Pleistocene seawater. (ii) radiogenic strontium isotopes in the deeper interstitial water indicate a deep fluid source that has reacted with the silicate component from the deep basin. (iii) the consistency of Sr isotopic compositions in the interstitial water and carbonate is observed when the authigenic carbonates precipitate from the pore fluids. (iv) the less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the carbonate reflect the terrestrial carbonate source carried by the Brazos and Trinity rivers.

5.2 Fluid flow and mixing in the over-pressured Ursa Basin

Based upon the Sr isotopic composition and concentration of the interstitial water at Site U1322, the data are divided into two parts, above 50 m and below 50 m, both with good linear correlation shown in the $^{87}\text{Sr}/^{86}\text{Sr}$ versus $1/\text{Sr}$ plot (Fig. 5). Above 50 m, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the surface interstitial water is close to the modern seawater, then decrease to the minimum around the Seismic Reflector S10. The decreased $^{87}\text{Sr}/^{86}\text{Sr}$ ratio with depth at Site U1322 is different to the constant ratio at Site U1319. Below 50 m, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the interstitial water increases with depth until the Seismic Reflector S40, then keeps constant between Seismic Reflector S40 and S60, a slightly decreased ratio is observed at the bottom of the core. The trend of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio varied with depth below 50 m at Site U1322 is similar to that of Site U1319 below 31 m, indicating the deep fluid might also experience the water-rock interaction.

Many researchers (e.g. Byrd et al., 1996; Flemings et al., 2006; Li and Jiang, 2010) have described the existence of shallow fluid flow phenomena in the Ursa Basin. Large pore water chemical variations

were observed around Seismic Reflector S10 (Flemings et al., 2006). The lateral fluid incursion along Seismic Reflector S10 in the over-pressured Ursa Basin is enriched in Cl^- , SO_4^{2-} , Na^+ , Mg^{2+} , B^{3+} , Ca^{2+} , Sr^{2+} , Li^+ and elevated $\delta^{11}\text{B}$ values (Li and Jiang, 2010). It has less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

The combination of Sr isotopes with classic chemical and isotopic techniques has been shown to be an appropriate approach for studying brine origin, the chemistry of which is modified by diagenetic processes altering the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio inherited from seawater or salts (Morton and Land, 1987; Stein et al., 2000; Kloppman et al., 2001; Reitz et al., 2007). Brines in the Gulf of Mexico may have two possible origins: (1) subsurface dissolution of evaporite minerals e.g. halite (NaCl) (Joye et al., 2005; Lapham et al., 2008), or (2) upward advection of relict Jurassic seawater that evaporated to the point of halite saturation and buried together with the evaporites that precipitated out of it (Aharon et al., 1992). The Jurassic seawater has a low $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7068 to 0.7076 (Burke et al., 1982; Veizer, 1989), but the Louann salt has a higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70838 (Stueber et al., 1984). This difference implies that the Jurassic saline fluid strontium isotopes became modified (more radiogenic) by either mixing with continental fluids or by diagenetic fluids of terrigenous sediments. This in turn may influence significantly the $^{87}\text{Sr}/^{86}\text{Sr}$ value of the pore fluids. Along Seismic Reflector S10, the lateral fluid incursion has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7081, i.e. slightly less radiogenic than the Louann salt but significantly more radiogenic than the Jurassic seawater. Therefore, it is likely that the source of the fluid may have been influenced by dissolved halite.

Below 50 m, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the interstitial water increases with depth until the Seismic Reflector S40, then keeps constant between Seismic Reflector S40 and S60, a slightly decreased ratio is observed at the bottom of the core. The maximum of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.70967) at Site U1322 is supposed another lateral fluid with more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio flows along the Seismic Reflector

S40. The variation of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the interstitial water at Site U1324 (Fig.2) was also observed the maximum $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.71000) around Seismic Reflector S40. Direct fluid pressure measurements at IODP308 U1324 defined the upward flow and downward flow beginning at the depth of 200 m at Site U1324 (Flemings et al., 2008). A lateral flow with radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ is necessary to supply the upward/downward flow end at Site U1324, we suggest it is around the Seismic Reflector S40 (about 320 m) based upon the Sr isotopic composition of the interstitial water. The more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the interstitial water at Site U1324 than Site U1322 indicates that the lateral fluid should flow from high to low pressure along the Seismic Reflector S40. In addition, downward migration of fluids at Site U1324 could also drive fluid flows laterally along the Blue Unit (Flemings et al., 2008), eventually fluids are discharged vertically upward to seafloor near Site U1322. The similar Sr isotopic composition of the bottom interstitial water at Site U1322 and U1324 confirmed that the lateral flow in the Blue Unit connects the two sites. A two-dimension fluid-flow model (shown in Fig.6) in the Ursa Basin is modified from Flemings et al. (2006) based upon the Sr isotopic composition of the interstitial water. Along the Seismic Reflector S10 and S40, lateral fluid flow from Site U1324 to U1322. Around Seismic Reflector S10, the lateral fluid had been modified by the dissolution of halite with less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$. But the lateral fluid along the Seismic Reflector S40 had experienced water-rock interaction, characterized with more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$. Pressure drives the lateral fluid upward and downward flow at Site U1324. The upward flow mixed with the less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ fluid, the downward migration of fluid could drive fluids laterally along the Blue Unit. Eventually fluid is discharged upward at Site U1322.

5.3 The deposition history of Ursa Basin

At Site U1322, the variations of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of carbonate and interstitial water show a similar

variation trend between them except at depth of 8.5 m and around Seismic Reflector S10 (Fig.2). The authigenic carbonate in the marine sediment should record the signal associated with precipitation from the interstitial water. Comparing the Sr isotopic composition in the interstitial water with carbonate, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the carbonate is less radiogenic than the interstitial water. Terrestrial carbonate with a lower radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio supplied by Mississippi River can reduce by about 0.0005 of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the carbonate. Xu and Marcantonio (2004) reported the Sr isotopic composition of the ion-exchangeable and terrestrial carbonate fractions from the Mississippi River, ranging from 0.7091 to 0.7096. The Mississippi River is not a single homogeneous unit, as there are many river confluents. The Red River originates in Texas, which is a tributary of the Mississippi River. Halite dissolution is a major influence within the Red River, with the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the waters ranging from 0.7076 to 0.7097 (Sun et al., 2011). The Mississippi River confluent with the Red and Atchafalaya rivers at Louisiana. Cretaceous carbonates ($^{87}\text{Sr}/^{86}\text{Sr}=0.7070-0.7075$) are carried into the Gulf of Mexico. Hence the less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of carbonate may be related to the terrestrial carbonate input.

Around Seismic Reflector S10 and at a depth of 8.5 m, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (about 0.7081) of the carbonate is less radiogenic than the interstitial water (0.7097). This may be related to the depositional history of the Ursa Basin. The Mississippi River drains presently North America between the Appalachian and Rocky Mountains. However during the late Pleistocene its drainage included Laurentide ice sheet and large glacial lakes such as the Lake Agassiz (Licciardi et al., 1999). Oxygen isotope records provide evidence that the Gulf of Mexico was the principal destination of pulsed meltwater discharges from the receding Laurentide ice sheet. Aharon (2006) estimated that one hyperpycnal flow event may have reached exceptional proportions (0.28 to 0.33 Sv) at 14.7 to 14.2 kyr. It is 9-10 times higher than the 0.0032 Sv peak flux of the Mississippi River great flood of the summer

of 1993 (Walker et al., 1994). The age of sediments around Seismic Reflector S10 and at 8.5 m at Site U1322 respectively are 14-15 ka and 9-10 ka based upon the planktonic foraminifer datum (Flemings et al., 2006). The depth of Seismic Reflector S10 at Site U1322 is about 28-34 m, corresponding to a 3% increased porosity. This depth correlates with the silt laminae interval at the base of lithostratigraphic Subunit IA (Seismic Reflector S10). Gilhooly et al (2008) have reported the carbon isotopic composition of sedimentary organic carbon at Site U1322. The minimum of $\delta^{13}\text{C}$ (-27.6 ‰) is located at the top of Seismic Reflector S10. This suggests a significant input of terrestrial organic material. Hence Seismic Reflector S10 may relate to meltwater discharges from the receding Laurentide ice sheet during an interval corresponding broadly with the time of the mwp-1A event (Fairbanks, 1989; Aharon, 2003). On the other hand, at a depth of 8.5 m, the $\delta^{13}\text{C}$ value of organic carbon is not its lowest, but highly ^{13}C and ^{18}O -depleted freshwater flow is recognized based upon $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of the planktonic foraminifer (Li et al., 2008). Such a flow is interpreted to correspond to intervals of low salinity, related with a large freshwater input, coinciding with the time of mwp-1B (Fairbanks, 1989). In summary, the less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ of the carbonate should relate to freshwater discharges through the Mississippi River at Site U1322.

6. Conclusions

Based on a detailed study on strontium isotopic composition of the interstitial water and carbonate in the sediments from the normally- and over-pressured basins in the Gulf of Mexico, the following conclusions can be drawn:

- 1) Different diagenetic reactions and fluid flow patterns have modified the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the interstitial water in both the normally-pressured Brazos-Trinity IV Basin and the over-pressured

Ursa Basin.

2) In the normally-pressured Brazos-Trinity IV Basin, radiogenic strontium isotopes in the interstitial water indicate a deep fluid source that has reacted with the silicate component from the deep basin and the less radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the carbonate reflect the terrestrial carbonate source carried by the Brazos and Trinity rivers.

3) In the over-pressured Ursa Basin, around Seismic Reflector S10, less radiogenic Sr isotopic composition is observed both in the interstitial water and carbonate, which may record a lateral fluid incursion. This lateral fluid incursion may have originated from the seawater, but has been modified by diagenetic reactions such as the dissolution of carbonate and halite and adsorption of clay.

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Table 1 Sr isotopic composition of the interstitial water and carbonate at Site U1319.

LEG	SITE	HOLE	CORE	TYPE	SECT	TOP (cm)	BTM (cm)	Depth (m)	Sr ²⁺ (μM)	Interstitial water ⁸⁷ Sr/ ⁸⁶ Sr	Carbonate ⁸⁷ Sr/ ⁸⁶ Sr
308	1319	A	1	H	3	127	132	4.4	79.4	0.709182±6	0.708741±22
308	1319	A	2	H	1	145	150	6.0	75.2	0.709182±10	——
308	1319	A	2	H	3	145	150	9.0	73.7	0.709182±6	0.708514±12
308	1319	A	2	H	5	145	150	12.0	75.6	0.709167±4	——
308	1319	A	2	H	6	145	150	13.5	77.3	0.709171±8	——
308	1319	A	2	H	7	64	69	14.2	78.9	0.709177±4	——
308	1319	A	3	H	1	145	150	15.5	78.4	0.709181±4	0.709140±10
308	1319	A	3	H	2	145	150	17.0	80.4	0.709181±2	——

308	1319	A	3	H	3	145	150	18.5	86.0	0.709175±4	0.709163±10
308	1319	A	3	H	4	145	150	20.0	83.1	0.709196±6	——
308	1319	A	3	H	6	145	150	23.0	83.3	0.709188±6	——
308	1319	A	3	H	7	74	79	23.8	79.2	0.709191±6	0.709181±6
308	1319	A	4	H	3	145	150	28.0	87.3	0.709187±6	——
308	1319	A	4	H	4	145	150	29.5	79.3	0.709196±6	0.709217±8
308	1319	A	4	H	5	145	150	31.0	85.4	0.709206±8	——
308	1319	A	4	H	6	145	150	32.5	87.8	0.709212±6	——
308	1319	A	4	H	7	145	150	33.1	87.8	0.709227±8	——
308	1319	A	5	H	2	145	150	36.0	86.2	0.709227±8	0.708622±14
308	1319	A	5	H	3	145	150	37.5	88.4	0.709221±6	——
308	1319	A	5	H	4	145	150	39.0	88.0	0.709237±6	——
308	1319	A	5	H	5	145	150	40.5	89.3	0.709251±6	0.708953±10

308	1319	A	5	H	6	145	150	42.0	88.7	0.709256±6	——
308	1319	A	5	H	7	145	150	42.7	88.5	0.709273±6	——
308	1319	A	6	H	1	145	150	44.0	89.4	0.709248±8	——
308	1319	A	6	H	2	145	150	45.5	93.5	0.709255±6	0.709166±8
308	1319	A	6	H	3	145	150	47.0	90.8	0.709276±6	——
308	1319	A	6	H	4	145	150	48.5	90.3	0.709281±6	——
308	1319	A	6	H	5	145	150	50.0	95.7	0.709278±10	0.708837±10
308	1319	A	6	H	7	53	58	52.3	94.6	0.709304±6	——
308	1319	A	7	H	1	145	150	53.5	95.1	0.709324±6	——
308	1319	A	7	H	2	145	150	55.0	93.4	0.709324±6	0.709012±8
308	1319	A	7	H	3	137	142	56.5	88.5	0.709324±6	——
308	1319	A	8	H	3	137	142	66.0	94.0	0.709355±8	0.708967±8
308	1319	A	11	H	3	145	150	93.1	101	0.709478±8	0.709522±30

308	1319	A	12	H	2	137	142	102.2	104	0.709427±6	0.709162±18
308	1319	A	13	H	3	77	82	109.9	112	0.709435±6	0.709097±8
308	1319	A	14	X	2	136	141	117.6	106	0.709474±8	0.709231±10
308	1319	A	16	X	3	137	142	133.2	103	0.709536±4	0.709017±18
308	1319	A	17	X	3	145	150	142.8	100	0.709490±8	—

Table 2 Sr isotopic composition of the interstitial water and carbonate at Site U1322

LEG	SITE	HOLE	CORE	TYPE	SECT	TOP	BTM	Depth (m)	Sr ²⁺ (μM)	Interstitial water ⁸⁷ Sr/ ⁸⁶ Sr	Carbonate ⁸⁷ Sr/ ⁸⁶ Sr
308	1322	B	1	H	3	87	100	3.9	96.1	0.709102±8	0.708885±8
308	1322	B	2	H	1	145	150	5.5	103.0	0.709060±8	0.708613±8
308	1322	B	2	H	3	145	150	8.5	108.7	0.709062±10	0.708088±10

308	1322	B	2	H	5	137	142	11.4	118.4	0.708996±6	0.708767±12
308	1322	B	3	H	3	145	150	18.0	134.4	0.708940±8	0.708797±10
308	1322	B	3	H	5	137	142	20.9	138.2	0.708923±4	0.708758±10
308	1322	B	4	H	1	145	150	24.5	137.4	0.708900±6	0.708565±24
308	1322	B	4	H	3	137	142	27.4	140.4	0.708890±8	0.708589±24
308	1322	B	4	H	5	145	150	30.5	137.3	0.708893±8	0.708522±24
308	1322	B	5	H	1	145	150	34.0	134.5	0.708884±6	0.708198±24
308	1322	B	5	H	5	145	150	40.0	134.3	0.708884±8	0.708123±10
308	1322	B	6	H	2	145	150	44.2	129.0	0.708892±8	0.708174±14
308	1322	B	6	H	5	145	150	48.7	127.2	0.708872±8	——
308	1322	B	8	H	3	137	142	65.4	133.6	0.708958±8	0.708576±24
308	1322	B	10	H	3	137	142	84.4	125.3	0.709043±10	0.708791±8
308	1322	B	11	H	3	132	142	92.3	119.4	0.709134±8	0.708836±10

308	1322	B	12	H	3	132	142	103.3	108.9	0.709304±6	0.708724±8
308	1322	B	13	H	6	75	85	115.3	93.0	0.709422±8	0.708703±12
308	1322	B	14	H	3	140	150	120.7	90.5	0.709436±10	——
308	1322	B	15	H	3	134	144	129.1	86.0	0.709462±8	0.708850±8
308	1322	B	16	H	3	140	150	138.7	85.7	0.709480±8	0.708900±8
308	1322	B	17	H	2	28	38	143.8	85.5	0.709547±8	0.708876±16
308	1322	B	18	H	3	140	150	154.3	81.8	0.709618±8	0.709060±72
308	1322	B	19	H	3	132	142	162.1	81.0	0.709675±10	0.709883±26
308	1322	B	20	H	3	140	150	171.1	86.1	0.709694±10	0.709092±16
308	1322	B	21	H	3	132	142	178.8	88.7	0.709660±4	0.709164±14
308	1322	B	22	H	3	140	150	186.7	90.4	0.709626±6	——
308	1322	B	23	H	3	132	142	193.3	90.6	0.709649±8	0.709168±10
308	1322	B	24	H	1	140	150	199.9	89.6	0.709667±10	0.709284±26

308	1322	B	25	H	4	140	150	207.0	91.0	0.709663±10	0.709249±14
308	1322	B	27	H	3	140	150	218.5	91.3	0.709709±16	0.709304±4
308	1322	B	28	H	3	140	150	224.7	92.5	0.709643±8	0.709174±10
308	1322	B	29	H	3	132	142	231.4	87.3	0.709548±8	0.709220±6

Table 3 Sr isotopic composition of the interstitial water at Site U1324

LEG	SITE	HOLE	CORE	TYPE	SECT	TOP	BTM	Depth (m)	Sr ²⁺ (μM)	Interstitial water ⁸⁷ Sr/ ⁸⁶ Sr
308	1324	B	2	H	5	135	140	11.2	117.1	0.708885±8
308	1324	B	3	H	5	137	142	20.7	137.2	0.708872±6
308	1324	B	4	H	5	145	150	30.3	141.2	0.709003±12
308	1324	B	5	H	3	137	142	36.7	138.5	0.708961±8

308	1324	B	6	H	3	137	142	46.2	136.7	0.708881±12
308	1324	B	7	H	3	132	142	55.6	137.1	0.708838±8
308	1324	B	9	H	3	132	142	74.6	123.4	0.708895±24
308	1324	B	13	H	3	132	142	112.6	117.6	0.709163±6
308	1324	B	19	H	3	132	142	166.3	100.5	0.709259±10
308	1324	B	27	H	3	140	150	226.9	95.3	0.709392±16
308	1324	B	35	H	2	132	142	293.2	99.0	0.709499±8
308	1324	B	45	X	2	140	150	360.8	103.3	0.709924±14
308	1324	B	52	X	3	140	150	401.2	104.7	0.709902±10
308	1324	B	71	X	3	140	150	584	105.8	0.709605±10
308	1324	B	74	X	3	132	142	603.1	70.8	0.710165±10

Figure Captions:

Fig. 1 (a) Location of the normally-pressured Brazos-Trinity Basin and the over-pressured Ursa Basin. (b) 2-D schematic seismic profile of the Brazos-Trinity Basin IV and the sampling sites. (c) 2-D schematic profile of the Ursa Basin showing the sampling sites. (modified from [Flemings et al., 2006](#)).

Fig. 2 Profiles of Sr concentration of the interstitial water and the Sr isotopic composition in the interstitial water (hollow circle and triangle) and carbonate (black circle) at Site U1319, U1322 and U1324.

Fig.3. $^{87}\text{Sr}/^{86}\text{Sr}$ ratio vs. $1/\text{Sr}$ concentration of the interstitial water at Site U1319. On this plot, a linear correlation is evident (equation: $\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 0.7106 - 0.124 \frac{1}{\text{Sr}}$, $R^2 = 0.84$ for the red hollow triangles). Extrapolation to zero $1/\text{Sr}$ gives an end-member $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7106.

Fig.4. Calcium carbonate (CaCO_3) of the sediment, Sr/Ca and Mg/Ca of the interstitial water at Site U1319. Lithologic Units: green = mud/clay suggesting turbidite influx. blue = foraminifer-bearing clay suggesting the hemipelagic deposition, yellow represents the transitional interval. The red line located at a depth of 31 m. It is the top of the Unit VI.

Fig. 5. $^{87}\text{Sr}/^{86}\text{Sr}$ ratio vs. $1/\text{Sr}$ concentration of the interstitial water at Site U1322. On this plot, the data points are divided into two parts: above 50 m and below 50 m. A linear correlation is evident between ratio of $^{87}\text{Sr}/^{86}\text{Sr}$ and $1/\text{Sr}$ in both parts ($\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 0.7079 + 1.446 \times 10^{-1} \frac{1}{\text{Sr}}$, $R^2 = 0.88$ above 50 m,

$$\frac{{}^{87}\text{Sr}}{{}^{86}\text{Sr}} = 0.7084 + 7.034 \times 10^{-2} \frac{1}{\text{Sr}}, \quad R^2 = 0.93 \text{ below } 50 \text{ m. The point of intersection with } {}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.7088,$$

and Sr concentration is 170.7 μM).

Fig.6. A conceptual model of fluid flow in the over-pressured Ursa Basin (modified after [Flemings et al., 2006](#)).