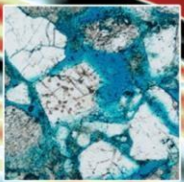
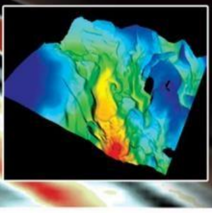
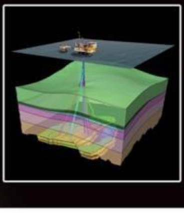

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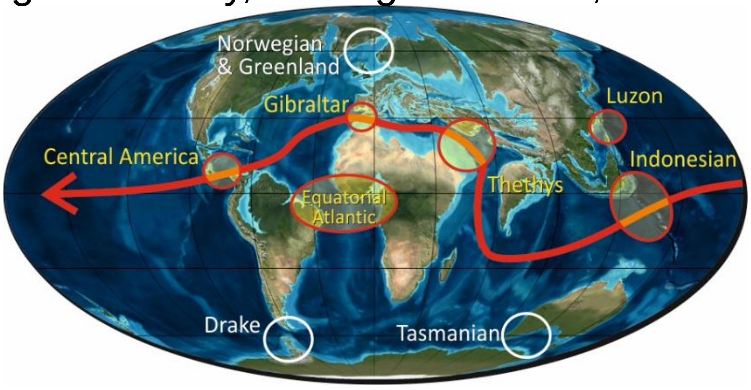
Oceanic gateways:
modern and ancient analogues and their conceptual and economic implications

23-25 November 2022

The Geological Society, Burlington House, Piccadilly London



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Sessions:

- Tectonic Controls on Gateways
- Oceanographic, Paleoceanographic and Sedimentary processes and deposits
- Gateways in polar regions
- Implications of gateways and contourite deposits on energy geosciences
- Data integration &multidisciplinary analysis

Keynotes:

- Oceanic gateways during the last 750 million years by *Christopher R. Scotese* (Northwestern Univ., USA)
- Paleoceanography and gateways by *André Bahr* (Heidelberg Univ., Heidelberg, Germany)
- Water masses circulation and oceanographic processes on gateways: the study case of the Strait of Gibraltar by *Ricardo F. Sánchez-Leal* (Spanish Institute of Oceanography, Spain)
- Sedimentary processes and deposits associated to gateways: a perspective from the ancient sedimentary record by *Heiko Hüneke* (Univ. Greifswald, Greifswald, Germany)
- Ichnological record on gateways and other high-energy deepwater environments by *Francisco J. Rodríguez-Tovar* (Univ. Granada, Spain)
- Fingerprints of geological-scale change in the Antarctic Circumpolar Current: insights from the present day by Alberto Naveira Garabato (Univ. Southampton, NOC, Southampton, UK)
- Southern ocean gateways and the development of the Antarctic Circumpolar Current by *Carlota Escutia* (IACT, CSIC-UGR, Spain)
- Implications of gateways and contourite deposits on energy geosciences by *Neil Hodgson and Karyna Rodriguez* (Searcher, UK)

Round table:

Oceanic gateways & energy geosciences. Chaired by *Adriano R. Viana* (Petrobras) & *Cindy Yeilding* (Ex-BP)

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OCEANIC GATEWAYS: MODERN AND ANCIENT ANALOGUES AND THEIR CONCEPTUAL AND ECONOMIC IMPLICATIONS

23 to 25 November 2022

The Geological Society (Burlington House, Piccadilly, London) & Virtual via Zoom

Schedules of this program are in London time zone

Day One	
08.30	***Registration***
08.50	**Welcome**
	Session One: **Tectonic Controls on Gateways**
09.00 **Virtual**	*Keynote:* **OCEANIC GATEWAYS DURING THE LAST 750 MILLION YEARS** **Christopher R. Scotese** *(Northwestern University, USA)*
09.40	**Mesozoic and Cenozoic Oceanic gateways evolution and global tectonics: palaeoceanographic and sedimentary implications** F. Javier Hernández-Molina *(Royal Holloway University of London, UK)*
09.55 **Virtual**	**The location and timing of the Early and Middle Jurassic Atlantic-Pacific Oceanic Gateway: An Open and Shut Case** Frank J. Peel *(The University of Texas at Austin, USA)*
10.10	**Geological evidence for Late Cretaceous emergence of the Panama island arc and palaeoceanographic implications** David M. Buchs *(Cardiff University, UK)*
10.25 **Virtual**	**Cenozoic palaeogeography of the Tethys and West Siberian Seaway: Implications of plate kinematics and dynamic topography on ocean circulation and climate** Eivind Olavson Straume *(The University of Texas at Austin, USA)*
10.40 **Virtual**	**Ocean gateways along transform margins and transform marginal plateaus** Lies Loncke *(CEFREM, Perpignan, France)*
10.55	***Break & Posters***
11.15	**The kinematics of the first stages of opening of the Equatorial Atlantic realm: the final disruption of Africa and South America, and its recording in the conjugated Demerara and Guinea marginal plateaus** Thomas Lesourd-Laux *(Univ Brest, CNRS, Ifremer, France)*
11.30	**The opening and evolution of the Equatorial Atlantic Gateway: state of the art and future ocean drilling proposals** Uisdean Nicholson *(Heriot-Watt University, Edinburgh)*
11.45	**Implication of palinspastic reconstructions in the evolution of the central Mediterranean sills during the Messinian Salinity Crisis** Romain Pellen *(Univ Brest, CNRS, Ifremer, France)*
12.00	**Closure of the Central American Seaway: a review** Camilo Montes *(Universidad del Norte, Colombia)*
12.15	**Biogeographic mechanisms involved in the colonization of Madagascar by african vertebrates: rifting, rafting and runways** Daniel Aslanian (IFREMER-GEOOCEAN-GIPS)
12.30	***Lunch & Posters***
	Session Two: **Oceanographic, Palaeoceanographic and Sedimentary processes and deposits**
13.30	*Keynote:* **WATER MASSES CIRCULATION AND OCEANOGRAPHIC PROCESSES AT GATEWAYS: THE CASE STUDY OF THE STRAIT OF GIBRALTAR** **Ricardo F. Sánchez-Leal** *(Spanish Institute of Oceanography, Cádiz)*
14.10	**Contourite processes associated with the overflow of Pacific Deep Water within the Luzon Trough: conceptual and regional implications** Shaoru Yin *(Second Institute of Oceanography, China)*
14.25 **Virtual**	**Sea-level control on sedimentary evolution of the Taiwan Strait** Xin Shan *(First Institute of Oceanography, China)*

14.40 **Virtual**	**New data on sedimentary processes in the Charlie-Gibbs Fracture Zone area during the Late Pleistocene to Holocene** Evgenia Dorokhova *(Shirshov Institute of Oceanology, Russian Acad. of Sciences, Russia)*
14.55	**Sedimentary processes in the Discovery Gap (Azores—Gibraltar Fracture Zone, NE Atlantic)** Tatiana Glazkova *(Royal Holloway University of London, UK)*
15.10	***Break & Posters***
15.30 **Virtual**	*Keynote:* **SEDIMENTARY PROCESSES AND DEPOSITS ASSOCIATED WITH GATEWAYS: A PERSPECTIVE FROM THE ANCIENT SEDIMENTARY RECORD** **Heiko Hüneke** *(Universität Greifswald, Greifswald, Germany)*
16.10	**Mixed carbonate-siliciclastic contourite drift deposits associated with the entrance of an Atlantic-Mediterranean corridor (late Miocene, southwest Spain)** Jesús Reolid *(Departamento de Estratigrafía y Paleontología, Universidad de Granada)*
16.25	**Mixed carbonate–siliciclastic tidal sedimentation in the Mediterranean-Atlantic connection through the Zagra Strait (Betic Cordillera)** Ángel Puga-Bernabéu *(Departamento de Estratigrafía y Paleontología, Univ. de Granada)*
16.40 **Virtual**	**Closing of the Betic-Rif corridors: considerations from the Late Miocene evolution of the Gulf of Cadiz** Zhi Lin, Ng *(Royal Holloway University of London, UK)*
16.55 **Virtual**	**Investigating Miocene Mediterranean-Atlantic Gateway Exchange (IMMAGE): an amphibious drilling project** Rachel Flecker *(University of Bristol, UK)*
17.10	***General discussion (Session One)*** Chaired by Eleanor Stirling (BP); and Giancarlo Davoli (Eni SpA)
17:30	**End of day one**
17:30-18:30	**Drinks reception**

Day Two	
08.30	***Registration***
08.50	**Welcome**
	Session Two: **Oceanographic, Palaeoceanographic and Sedimentary processes and deposits**
09.00	*Keynote:* **PALAEOCEANOGRAPHY AND GATEWAYS** **André Bahr** *(Heidelberg University, Heidelberg, Germany)*
09.40	**Seismic stratigraphy of the Guinea plateau: a 150-Myr history of structural deformation, sediment routing and magmatism** Benedict Aduomahor *(Heriot-Watt University, Edinburgh)*
09.55 **Virtual**	**Impact of the Pyrenean Gateway on deep-water circulation in the NE Atlantic during the Middle and Late Cretaceous** Shan Liu *(School of Marine Science, Sun Yat-sen University, China)*
10.10	**Late Cretaceous palaeotemperature records from the Australian southern margin: a link between temperature and the opening of the Australo-Antarctic Gulf?** Lauren K. O'Connor *(University of Manchester, UK)*
10.25 **Virtual**	**Bottom currents deposits in NW Australia: evidences of the onset and evolution of the Australia - Indian Ocean Gateway** Oswaldo Mantilla *(Ecopetrol S.A, Colombia)*
10.40 **Virtual**	**Contourite depositional systems within the Orange Basin, South Africa** Anthony Fielies *(Petroleum Agency SA)*
10.55	***Break***
11.15 **Virtual**	**The impact of Atlantic palaeogateways on the growth of ancient mixed depositional systems: palaeoceanographic, sedimentary and economic implications** Sara Rodrigues *(Royal Holloway University of London, UK)*
11.30	**Eocene to middle Miocene contourite deposits in Cyprus: a record of Indian Gateway evolution** F. Javier Hernandez-Molina *(Royal Holloway University of London, UK)*
11.45 **Virtual**	**The late Miocene Panamanian Isthmian strait was shallow** Elena Stiles *(Universidad del Norte, Colombia)*

12: 00	***Lunch & Poster***
13.00 Virtual	*Keynote:* **ICHNOLOGICAL RECORD ON GATEWAYS AND OTHER HIGH-ENERGY DEEPWATER ENVIRONMENTS** **Francisco J. Rodríguez-Tovar** *(Universidad de Granada, Spain)*
	Session Three: **Data integration &multidisciplinary analysis**
13.40	**Mapping Ocean Gateways from 3D Seismic Data: Modern Seafloor and Ancient Analogues** Andreas Laake *(Schlumberger, Germany)*
13.55	**Using seismic data to image water masses – sedimentation interactions at the Demerara plateau offshore Surinam and French Guyana.** Thomas Lesourd-Laux *(Univ Brest, CNRS, Ifremer, France)*
14.10	***General discussion (Session Two & Three)*** Chaired by Domenico Chiarella and F. Javier Hernández-Molina (RHUL)
15.00	***Break & Posters***
16.30	**End of day two**
19.30	***Dinner – to be offsite and arranged separately of the Geological Society – more details to follow***

Day Three	
08.30	***Registration***
08.50	**Welcome**
	Session Four: **Gateways in Polar regions**
09.00 Virtual	*Keynote:* **FINGERPRINTS OF GEOLOGICAL-SCALE CHANGE IN THE ANTARCTIC CIRCUMPOLAR CURRENT: INSIGHTS FROM THE PRESENT DAY** **Alberto Naveira Garabato** *(Univ. Southampton, National Oceanography Centre, UK)*
09.40	**Modelling the role of seabed topography in the life and fate of dense overflows in Antarctica** David Amblas *(Department of Earth and Ocean Dynamics, Univ. of Barcelona, Barcelona*
09.55	**The role of Southern Ocean gateway opening in the evolution of Southern Ocean surface oceanography: latitudinal gradients, subpolar gyres and the Antarctic Circumpolar Current** Frida. S. Hoem *(Department of Earth Science, Utrecht University, Utrecht, the Netherlands)*
10.10	**IN PERSON / VIRTUAL** **IODP Expedition 382: a tale from scientific drilling in the Drake Passage** Lara F. Pérez *(Geological Survey of Denmark and Greenland, Denmark)*
10.25	**Does tectonics or climate control Atlantic Meridional Overturning Circulation through the Greenland-Scotland Ridge oceanic gateway?** Stephen M Jones *(School of Geography, Earth & Environmental Science, University of Birmingham, UK)*
10.40	**Underexplored continental shelf gateways: timing, mechanisms and role of SW Barents Sea Gateway, Norwegian Arctic** Amando P. E. Lasabuda *(Dept. Geosciences, The Arctic University of Norway, Norway)*
10.55	***Break & Posters***
11.15	*Keynote:* **SOUTHERN OCEAN GATEWAYS AND THE DEVELOPMENT OF THE ANTARCTIC CIRCUMPOLAR CURRENT** **Dimitrios Evangelinos** (Univ. Barcelona)
11.55	**Drake Passage opening: origins and dispersal of the continental fragments that formed the North and South Scotia Ridges** Andrew Carter *(London Geochronology Centre, UCL, London, UK)*
12.10	**Bering Strait gateway currents and effect on sediment distribution** Hans Nelson *(Instituto Andaluz de Ciencias de la Tierra, CSIC-UGR, Granada)*
12.25	**Timing and consequences of Bering Strait oceanic gateway opening: new insights from ^{40}Ar/^{39}Ar dating of the Barmur Group (Tjörnes beds), northern Iceland** Jonathan R Hall (*Univ. Birmingham, UK)*
12.40	***Lunch & Posters***
13.45	***General discussion (Session Four).*** Chaired by Lara Perez (GEUS); Kelly A. Hogan (BAS); Dimitrios Evangelinos (Univ. Barcelona) and Fernando Bohoyo (IGME).
	Session Five: **Implications of gateways and contourite deposits on energy geosciences**

14.30 **Virtual**	*Keynote:* **IMPLICATIONS OF GATEWAYS AND CONTOURITE DEPOSITS ON ENERGY GEOSCIENCES** **Neil Hodgson** and **Karyna Rodriguez** *(Searcher, UK)*
15.10 **Virtual**	**Entrapment and expansion of water masses in oceanic gateway-related environments and its implication for the birth of source rocks: sedimentary geochemistry from the Permian and Aptian/Albian Gondwanan geological record** Lucas Pinto Heckert Bastos *(Rio de Janeiro State University, Rio de Janeiro, Brazil)*
15.25 **Virtual**	**Sedimentology and ichnology of Upper Jurassic to Lower Cretaceous contourites in an unconventional shale reservoir (Vaca Muerta Formation, Argentina)** Maximiliano Paz *(Department of Geological Sciences, University of Saskatchewan, Canada)*
15.40	***Break & Posters***
16.00 **Virtual**	**The contourite depositional systems in the offshore basins of Sulawesi and their implications for reservoir distribution** Cahyagempita Agustina Putri *(Pertamina Hulu Energi)*
16.15	**Hydrocarbon potential seismic evaluation of hybrid turbidite contourite systems** Karyna Rodriguez and Neil Hodgson *(Searcher, UK)*
16.30	**"ROUND TABLE": OCEANIC GATEWAYS & ENERGY GEOSCIENCES** Chaired virtual by Adriano R. Viana (*Petrobras, Brazil*) and Cindy Yeilding (*Ex-BP, USA*
17.30	***Closing***
17:35	**End of Conference**

Posters	
Session Two	**Bottom-current morpho-sedimentary features of the Messina Strait** Eleonora Martorelli *(CNR-IGAG, Rome, Italy)*
	Facies-based tidal strait model and implications for interpreting ancient gateways Sergio G. Longhitano *(Univeristà degli Studi della Basilicata, Italy)* & Domenico Chiarella *(Royal Holloway University of London, UK)*
	Echo-character distribution with respect to bottom current pathways in the Western Gap (Azores—Gibraltar Fracture Zone, NE Atlantic) Tatiana Glazkova *(Royal Holloway University of London, UK)*
	Contourites in the eastern part of the Vema Fracture Zone (Tropical Atlantic) Dmitrii G. Borisov *(Shirshov Institute of Oceanology, Russian Academy of Sciences, Russia)*
	Deep-sea terrigenous and biogenic calcareous contourite systems around the northern exit of the Vema Channel Elena V. Ivanova *(Shirshov Institute of Oceanology, Russian Academy of Sciences, Russia)*
	Late Miocene to Quaternary bottom current deposits in the Gulf of Cadiz related to the Mediterranean - Atlantic exchange evolution: decoding bottom currents behaviour and oceanographic processes associated with gateways F. Javier Hernandez-Molina *(Royal Holloway University of London, UK)*
	Contourite channels and gateways: the study case of the late Miocene South Riffian Corridor, Morocco Wouter de Weger *(Royal Holloway University of London, UK)*
	Contourite (palaeo)channels and gateways: evidences of the intermittent MOW circulation after the opening of the Gibraltar Strait Estefanía Llave *(Instituto Geológico y Minero de España, IGME-CSIC, Spain)*
Session Four	**Contour current deposition in the South Orkney Microcontinent (southern Scotia Arc, Antarctica) and their link with the opening and evolution of the Drake Passage** Cecilia Morales-Ocaña *(Instituto Andaluz de Ciencias de la Tierra, CSIC-UGR, Granada)*

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ORAL ABSTRACTS
(In Programme Order)

Session One: Tectonic Controls on Gateways

Keynote – Christopher R. Scotese

Oceanic Gateways During the Last 750 Million Years

Department of Earth & Planetary Sciences, Northwestern University, Evanston, IL, 60208, USA

Contact email address: cscotese@gmail.com

The rifting and collision of continents during the last 750 million years has resulted in the opening and closing of more than 50 oceanic gateways. Approximately 20 through-going oceanic seaways have closed as continents have collided (e.g., collision of the Congo craton with Eastern Gondwana (600 Ma), the closure of the Rheic Ocean to form Pangea (300 Ma), or the collision of Australia with Southeast Asia (12 Ma). Conversely, ~30 new seaways have opened as a result of continental rifting and the formation of new ocean basins (e.g., the opening of the Iapetus Ocean (570 Ma), the rifting of Cimmeria from the Indo-Australian margin of Gondwana (300 Ma), and the separation of Australia from Antarctica (40 Ma)).

The paleolatitude of these gateway events determines how these events will affect global oceanic circulation and climate. There have been a roughly equal number of high latitude events (60 – 90 NS), intermediate latitude events (45 – 60 NS), and low latitude events (0 – 30 NS). The orientation of the closing or opening seaways is also important. Approximately 2/3 of the seaways have been oriented parallel to lines of latitude (i.e, E-W). These seaways have often connected or blocked major E-W flowing ocean currents. In contrast, seaways that have been oriented N-S, have had little effect on ocean circulation but have played an important role in the transport of heat from the Equator to the poles (e.g., the evolving Gulf Stream).

In this presentation, we will review the location and timing of major oceanic gateways, we will describe the effects that these paleogeographic changes have had on ocean circulation and climate, and we will present an animation of oceanic gateway evolution since the middle Neoproterozoic (~750 Ma).

Mesozoic and Cenozoic Oceanic gateways evolution and global tectonic: paleoceanographic and sedimentary implications

Hernández-Molina, F.J., Scotese, C. R.

[1] *Dept. Earth Sciences, Royal Holloway Univ. London, Egham, Surrey TW20 0EX, UK*
[2] *Department of Earth & Planetary Sciences, Northwestern University, Evanston, IL, 60208, USA*

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Ocean basins are connected by gateways (e.g., Drake Passage), sometimes referred to as seaways, passages, straits, and corridors. The evolution of these oceanic gateways depends on plate tectonic evolution, but despite of their importance of these gateways, there remains considerable uncertainty concerning the geological and oceanographic / paleoceanographic processes that occurred within and around them. Their evolution has been influenced the global ocean circulation and the vertical structure of water masses, conditioning the onset, growing and buried of both contourite and mixed sedimentary systems.

The modern model of geostrophic circulation induced by global thermohaline circulation maintain that deep water formation takes place in localized areas, the most important being those located in the polar regions. This current circulation model was established between the Miocene (~13 Ma) to the base of the Quaternary (2.6 Ma) with the final closure of the Central America Seaway (CAS), which ended the transition from the warm greenhouse climate of the Late Cretaceous and early Cenozoic to the predominance of northern hemisphere glaciations during the Quaternary. The global circulation of water masses in the geological past was very different from the current model and their evolution is directly related to plate tectonics and gateways evolution (Fig. 1), which key events are,

- Establishment of the global westward equatorial circulation and eastward circulation in the southern hemisphere (latest Jurassic – early Cretaceous).
- Opening and later deepening of the Equatorial Atlantic Seaway (mid Cretaceous) – enhanced of water masses circulation in the southern oceans
- Opening of the Tasman Seaway (late Eocene) - initial development of the Antarctic Circumpolar Current (ACC) around part of Antarctica.
- Opening of the Drake Passage (late Eocene/early Oligocene) - full development of the Antarctic Circumpolar Current (ACC) which contributes to the climatic isolation of the continent, the onset of ice accumulation in Eastern Antarctica and the final initiation of the Antarctic Bottom Water (AABW).
- Opening of a deepwater connection between the Arctic and the North Atlantic (early to middle Miocene) - full initiation of the North Atlantic Deep Water (NADW).
- Closure of the Indian Gateway (middle Miocene) that represented the end of the global equatorial circulation and the Mediterranean Sea contribution to the Atlantic Meridional Overturning Circulation (AMOC). Closure coincided with a period of major global climatic and oceanographic changes during the Middle Miocene Climatic Transition (MMCT) from approximately 14.2 to 13.8 Ma.
- Closure and opening of the Strait of Gibraltar (late Miocene and early Pliocene) - initiation of the present-day Mediterranean Outflow Water (MOW) with enhanced Meridional Overturning Circulation (MOC).
- Closure of the Indonesian seaway (late Miocene) with the final connection between the Pacific and Indian oceans.
- Closure of the Central American seaway (late Pliocene / early Quaternary) - final establishment of the Gulf current and onset of ice accumulation in the Arctic, an event that amplifies climatic variations.

- Both glacial stages and terminations of glacial stages bring higher production and spreading of saltier, more voluminous AABW. By contrast, the NADW experienced spreading and enhanced circulation during interglacial stages.

The structure of the ocean was considerably simpler in the past and has become progressively more complex due to the opening and closing of the gateways and the climatic evolution of the planet. These global changes have conditioned the exchange of water masses between ocean basins and therefore global circulation, so that the appearance of new water masses and their subsequent evolution would determine the development of: a) huge contour systems within abyssal plains during the Mesozoic; b) large deposits along the lower slope from the Paleogene to the middle Miocene; c) migrations of these deposits towards the middle slope and continental rise during the Upper Miocene; and d) development of new deposits along the upper slope since the beginning of the Pliocene. Therefore, the global paleoceanographic evolution would determine the sedimentary evolution and the morphology of the marine basins.

The initiation and burial of these sedimentary systems depend on long-term (>5/10 Ma) variations in paleocirculation driven by opening/closing, or deepening/shrinking of gateways and other events related to plate tectonics. These tectonic events, as well as others on a smaller scale (a few million at > 0.4 Ma), have been related to variability in mantle convective activity. Changes in ocean circulation of ~0.8 to 0.9 Ma in duration, superimposed on changes of 2 to 2.5 Ma, have been described and are attributed to such tectonic pulses and have been related to the formation of sedimentary hiatus and changes in sedimentary architecture within contouritic and mixed systems. On shorter time scales (<0.4 Ma), climatic and eustatic changes, modulated by planetary orbital variations, influence sedimentary cyclicity and the vertical and spatial distribution of these deposits.

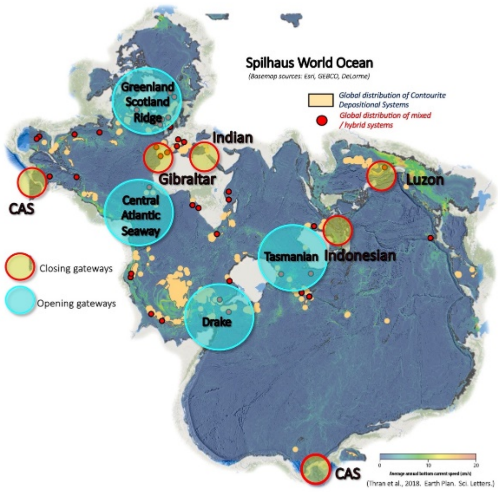

Figure 1. Distribution of important gateways during the Cenozoic. Closing gateways indicated in yellow and opening gateways indicated in blue. Closing and opening of gateways can induce drastic changes in deepwater circulation, determining the onset of the modern global thermohaline circulation and formation of contourite and mixed systems (from Hernández-Molina, F.J. et al 2022).

Hernández-Molina, F.J. et al 2022. Chapter 9: Contourites and mixed depositional systems: a paradigm for deepwater sedimentary environments. In: Deep-Water Depositional Systems. (Eds.: Rotzien, J.R., Yeilding, C., Sears, R., Catuneanu, O., Hernández-Molina, F.J.,). Elservier. *In press,* 2022

Scotese, C., 2019. Plate Tectonics Paleogeography & Ice ages. Paleomar Project http://www.scotese.com

This project was funded by the Joint Industry Project supported by TOTAL, BP, ENI, ExxonMobil, Wintershall Dea and TGS within the framework of “The Drifters Research Group” at Royal Holloway, University of London (RHUL).

The location and timing of the Early and Middle Jurassic Atlantic-Pacific Oceanic Gateway: An Open and Shut Case

Frank J Peel[1], Gillian M Apps[1] and Andrew Pulham[2]

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[2]Independent Consultant, Boulder CO Frank.peel@beg.utexas.edu

It has long been established that development of a Circum-Equatorial marine connection in the Jurassic, connecting Tethys to Pacific, would have had a powerful effect on the global paleo-oceanographic system, climate, and biogeography. While there is regional biostratigraphic evidence for such a Tethys-Pacific marine connection at times during the Early and Middle Jurassic, there has been very poor constraint on its location, or on the timing of its opening and closing. The putative connection has been named the “Hispanic Corridor” and conventionally this has been drawn, with little direct evidence, through the Proto-Caribbean and the terrains that would later assemble to form Mexico. Conveniently, direct evidence of such a “Hispanic Corridor” is destroyed by subduction of the Paleo-Caribbean.

Conventional wisdom also held that the early Gulf of Mexico (GoM) basin did not see any influx of marine water before the Callovian, and that an E-W oceanic connection through the GoM was not established until the Oxfordian.

However, new information challenges all of these preconceptions: we can demonstrate that the GoM was connected to the Tethys much earlier. A dessicated pre-Salt GoM basin was inundated with ocean brine at 170MA (Bajocian), leading to the deposition of the Louann Salt Giant which is dated using Sr_{87}/Sr_{86} data; marine connection was then lost, leading to basin desiccation lasting for ca. 5Myr, and then re-established, with probable formation of a connected E-W Tethys-Pacific oceanic gateway through the GoM, in the Callovian.

Seismic evidence indicates that before this, there had been at least one previous period during which the GoM basin contained a >1km deep water body whose surface was at or near global sea level, suggestive of a marine connection, and that this Early Jurassic marine GoM basin had subsequently been isolated and evaporated at least once prior to 170MA. The Early Jurassic proto-GoM was connected to Tethys via the Atlantic rift system, along the eastern margin of North America and continuing through the Georgia Rift basins. In contrast, recent plate reconstructions do not favor the existence of a connected rift basin system along the conventional “Hispanic Corridor’ at this time, not beginning until late Middle Jurassic. The Tethys-Pacific shallow water faunal connection in the Toarcian indicates that the pre-salt marine episode in the GoM at least overlaps in age with the Toarcian.

We therefore propose a new model in which the Tethys-Pacific connection was opened and closed repeatedly during the Early and Middle Jurassic, not initially through the conventional “Hispanic Corridor”, but instead connecting the two oceans further north, through the proto-Gulf of Mexico. At times in the Early Jurassic, we propose a GoM marine gateway to the Tethys via the Florida-Georgia rift system, while in the Middle Jurassic the marine connection was via the proto-Straits of Florida.

The post-Aalenian sediment record within the deepwater GoM indicates a progressive deepening of the oceanic gateway connections to the GoM, so that throughout the Jurassic these were silled, with shallow water connections allowing faunal throughput, while the water in the deep GoM basin was not flushed. Around the end of the Jurassic, the gateway connections deepened, allowing deep currents to flush the basin deeps.

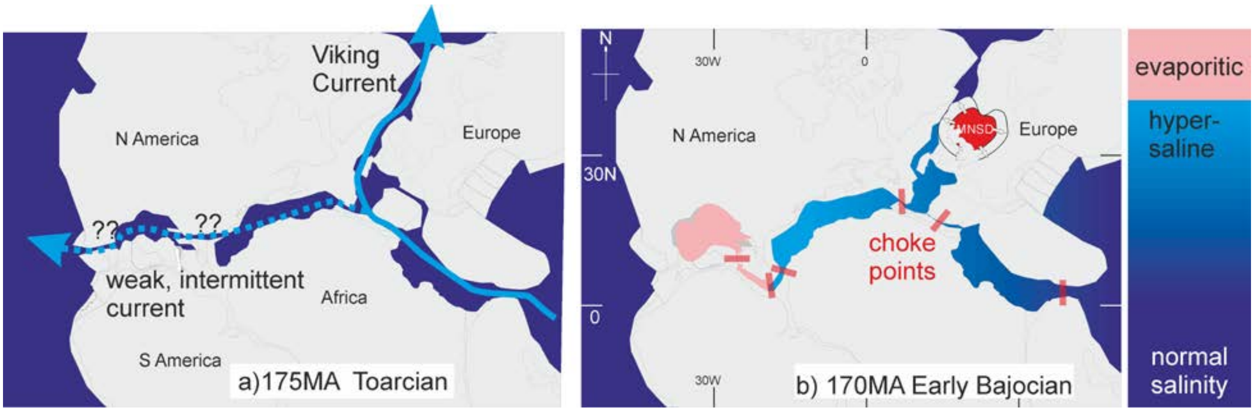

Figure 1: (a) Oceanic gateway connection paths in the Toarcian via the Georgia Rift System; (b) in Early Bajocian via the Straits of Florida.

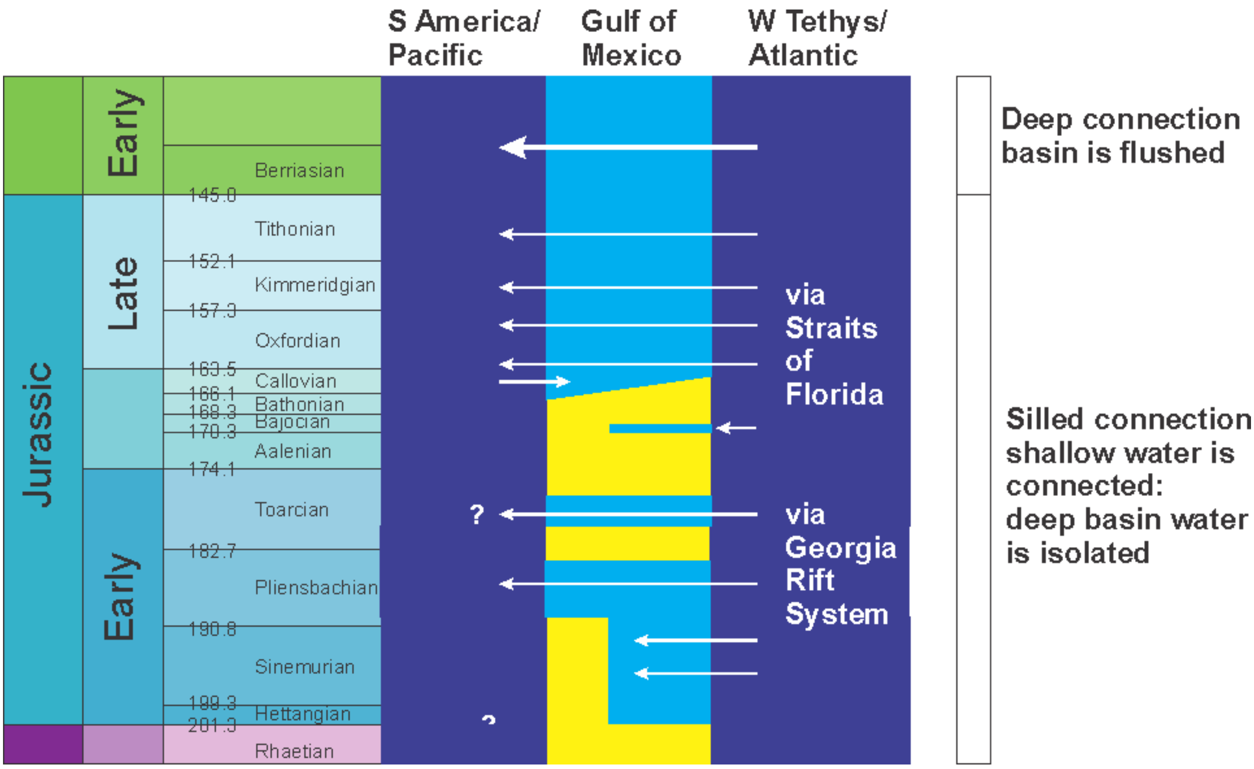

Figure 2: Timing of opening and closing of the Tethys/Pacific Oceanic Gateway. Yellow=closed

Geological evidence for Late Cretaceous emergence of the Panama island arc and palaeoceanographic implications

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The formation and emergence of the Isthmus of Panama is among the most fundamental geological events in Earth's recent history, with significant implications for the connection of North and South American ecosystems and global palaeoceanographic conditions during the Neogene. The formation of the Isthmus, which connected terrestrial environments in the Americas and ceased direct connection between the Atlantic and Pacific Oceans, is generally believed to have occurred in the Pliocene (ca. 3 Ma ago) in response to the collision of the Panama volcanic arc with South America (Coates et al., 2004). Emergence of the Isthmus is thought to have triggered the onset of a new (still on-going) climatic regime in the northern hemisphere (Haug and Tiedemann, 1998), and facilitated migration of terrestrial organisms between the Americas (i.e., the Great American Biotic Interchange) (Marshall et al, 1982). New tectonic constraints suggest that the emergence of the Isthmus could already have occurred in the middle Miocene (13-15 Ma ago) (Montes et al., 2015), although this interpretation seems at odds with some of the paleontological and palaeocenographic evidence (O'Dea et al., 2016). Limitation in our understanding of the formation of the Isthmus is mostly due to the use of indirect environmental, biologic and tectonic proxies, whereas field constraints required to directly characterise the palaeogeographic evolution of the Isthmus lack over considerable areas of the Panama volcanic arc. We addressed this issue by conducting regional exploratory field work, geochemical analyses, and paleontological and geochronological dating in Panama and Colombia to reconstruct regional volcanic history that contributed to the emergence of the Isthmus (GRIP project, https://panamageology.wordpress.com/). We then ran a series of numerical simulations using coupled atmosphere-ocean Earth System Model COSMOS to evaluate palaeoceanographic effects of our new field-based palaeogeographic constraints.

Our results reveal four main regional volcanic phases that contributed to shoaling and local emergence of Panama as early as the Late Cretaceous. The earliest documented emergence in Panama is evidenced by Campanian (ca. 70 Ma) conglomeratic andesite deposits in a nascent island arc along the SW margin of Caribbean Plate. Rapid formation of islands was facilitated by development of the Panama volcanic arc on top of the Caribbean oceanic plateau, which served as a volcanic promontory for the southern Central American volcanic arc. Subduction initiation in Panama occurred ca. 20 Myr after emplacement of the Caribbean oceanic plateau, which was locally emergent and could have caused obstruction of oceanic currents in the inter-American seaway, ultimately triggering Oceanic Anoxic Event 3 in the early Atlantic Ocean (Buchs et al., 2018). Two main volcanic phases occurred in the Panama volcanic arc after subduction initiation, which contributed to the topographic growth of the Isthmus (Buchs et al., 2019). Long-term volcanic activity, arc-continent collision, and subduction tectonics acted together to contribute to the final emergence of the Isthmus in the Pliocene, with the possibility for a complex history of emergence/submergence at shorter time scales during the Neogene. Our numerical climate model simulations reveal that the early shoaling and local emergence of the Panama island arc could have modified palaeoceanographic conditions during the Late Cretaceous, notably affecting water flows between the early Atlantic and Pacific Oceans and increasing temperature at intermediate water depths in the Atlantic.

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Cenozoic paleogeography of the Tethys and West Siberian Seaway: Implications of plate kinematics and dynamic topography on ocean circulation and climate

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We present new detailed Cenozoic (66 – 0 Ma) paleogeographic reconstructions of the Tethys and West Siberian Seaway including updated paleogeography of Arabia and Eurasia, and new models for dynamic topography. Closing these seaways during the Cenozoic played a key role in shaping the modern global ocean circulation. However, the gradual shallowing and timing of closing the link between the Atlantic and Indo-Pacific Oceans are still debated, and the evolution and morphology of the West Siberian Seaway is not well known. The closure of the Tethys Seaway contributed to the development of the modern Atlantic meridional overturing circulation, while the opening and closing of a shallow seaway over Eurasia to the Arctic Ocean could have influenced Arctic Ocean salinity and freshwater leakage to the adjacent seas (through the North Atlantic – Arctic oceanic gateways and the West Siberian Seaway). This could have had profound effects on regional and global ocean circulation patters. Our results from ocean circulation modelling (using the NorESM, and the MITgcm) shows that bathymetric changes to these seaways were important for global ocean circulation changes since the Eocene. One general result is that a shallowing of the Tethys Seaway before the Eocene – Oligocene transition could have reduced the transport of Indo-Pacific waters to the North Atlantic and increased the salinity in the Atlantic Ocean; thereby increasing deep water formation in the North Atlantic before the gateway fully closed. Later, in the Miocene, changing dynamic topography may explain the proposed shallow and temporal connections between the Mediterranean and Indian Ocean. We also show that different paleogeographic configurations, depending on the choice of dynamic topography and kinematic model, can have significantly different impacts on modelled global ocean circulation and climate for the Cenozoic time.

Ocean gateways along transform margins and transform marginal plateaus

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The formation of oceanic realms follows continental breakup, in a fundamentally polyphased process. For example, the Gondwana Breakup that gave birth to the Atlantic, Indian, Artic and Antarctic oceans began in the Jurassic and ended in the Oligocene/Miocene. During this time-span, several ocean basins opened and progressively connected one to each other.

In most cases, transform plate boundaries formed between successive oceanic basins allowing their connection. A well-known example is the transform-dominated equatorial Atlantic gateway that formed during the lower Cretaceous a paleo-gateway between the Jurassic Central Atlantic and the lower Cretaceous South Atlantic.

When they develop, transform margins form last contact points between continents: at the time when oceanic accretion starts in divergent margins, the two continents are still in contact at a lithospheric scale on each side of the transform fault. For a spreading rate of 2 cm/year, the last continental contact is lost 5 Myrs after oceanic spreading started for a 100 km long transform, and 25 Myrs for a 500 km long transform, which represents a significant time lapse. From breakup to oceanic accretion, a transform zone evolves successively from a transform valley (for example the Dead Sea valley, intra-continental transform stage), to an isolated rhomboedric ocean basin (for example, the gulf of California, active transform margin stage), and finally a narrow ocean gateway (for example, the Cenomanian equatorial Atlantic gateway, during the passive transform stage, or more recently, the Miocene Fram straight). During the active and early passive transform stages, important vertical movements recorded by erosion surfaces and fission track data show that this lithospheric transform boundary can be associated to emersion (example of the Côte d'Ivoire Ghana Marginal Ridge or Demerara/Guinea plateaus in the late Albian). Later on, transform fault zones are particularly sensitive to any kinematic or thermal change that may allow submarine relief development that affect oceanographic bodies (examples of transpressional reactivations of the Romanche Fracture Zone (FZ), and volcanic effusives along the Davies or Guinea FZ).

Furthermore, planar submarine reliefs extending the continental shelf of transform margins are found off a third of the world's transform margins. Their mean water depths vary between 1200 to 3000 m and their areal extent can reach 300 000 to 570 000 km². Those reliefs have been called "Transform Marginal Plateaus" or "TMPs" (Loncke et al., 2020). 20 TMPs have been defined in the world (red boxes on figure 1). The most impressive of them is probably the Falkland-Malvinas plateau that reach ~ 1400 km in length (Figure 1 and 2). These TMPs mostly form at the junction of oceanic basins of contrasted ages and many of them underwent heavy volcanism and magmatism, probably related to hotspot activity in at least one of their evolution stages (e.g. Vøring, Walvis, Exmouth, Hatton-Rockall, Demerara/Guinea TMPs). Their crusts are in majority igneous or continental, heavily intruded by magmatic and volcanic bodies and some of them seem to correspond to thick or thickened oceanic crust domains. Many transform marginal plateaus were the last, or close to last, contacts during final continental breakup, some of them probably emerged, especially those that were volcanic margins that typically evolve in their first stages as aerial to very shallow basins. It is probably the case of the Vøring Plateau which remained connected to the Jan Mayen microcontinent/Greenland margin and the Faroe-Rockall/Newfoundland plateaus also connected until the late opening of the North Atlantic domain. The Walvis Plateau, Walvis Ridge and Sao-Paulo Plateau may also be good candidates for having formed another land bridge during the South Atlantic Ocean opening. Of course, TMPs may have been landbridges or shallow submarine elevations influencing biological connectivity and oceanographic conditions between continents after Gondwana or later breakup. At present day, they also influence oceanic circulation and seem to localize important contourite fields along their flanks.

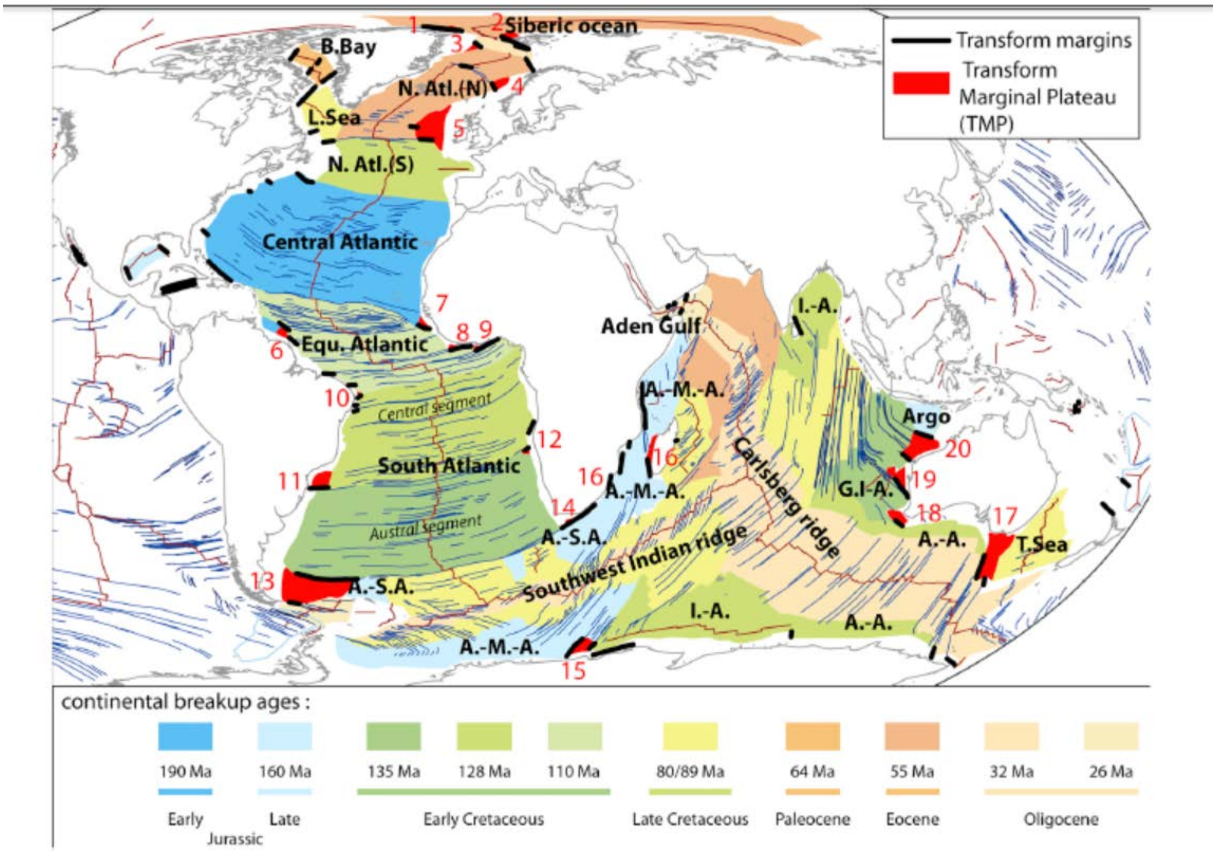

Figure 1 : Transform margins (thick black lines), transform marginal plateaus (red), and breakup ages (modified from Mercier de Lepinay et al., 2016. Most breakup ages are deduced from Muller et al., 2008 and Muller et al., 2016a, 2016b. Indian-Madagascar-Antarctic separation domains are from Marks and Tikku (2001) and Indian-Australia-Antarctic separation ages are from Gibbons et al. (2013). The Central Atlantic breakup age comes from Labails et al. (2010) and Davison and Dailly (2010)). In blue, oceanic fracture zones from Matthews et al., 2011.

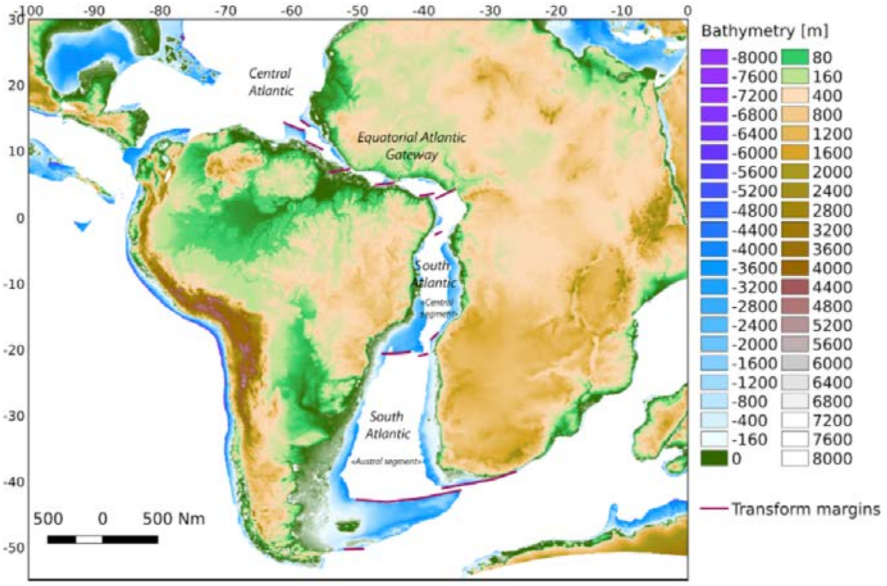

Figure 2 : Plate kinematic reconstruction of Africa/America respective positions at 110 Ma with South America fixed present-day bathymetry along TMPs and margins. Rotation poles and COB are from Matthews et al., 2016 and Torsvik et al., 2009.

The kinematic of the first stages of opening of the Equatorial Atlantic realm: the final disruption of Africa and South America, and its recording in the conjugated Demerara and Guinea marginal plateaus

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The kinematic of the rifting and initial oceanic opening of the Equatorial Atlantic Ocean has almost been a blind spot in the reconstructions of the separation of Africa from America. The only study devoted to this subject was the unpublished PhD thesis of Agnès Campan (1995), whose results were since incorporated in all publications (e.g. Moulin et al., 2010; Heine et al., 2013). The main reason for this lack of investigation is the lack of magnetic anomalies related to the first stages of oceanic opening, that occurred during the Cretaceous quiet magnetic period (83-118 Ma). Other reasons are the difficulty to record accurate magnetic measurements in the equatorial area, and the fact that the initial oceanic fracture zones are either partially or totally hidden, by the upper Cretaceous and Neogene volcanism of Guinea and Sierra Leone plateaus on the Africa side, and by the Caribbean subduction zone on the American side (Figure).

We used a detailed mapping of the fracture zones at the connection between the Equatorial and the Central Atlantic (Figure) to re-evaluate the published kinematic reconstructions. In this area, as Campan (1995) noticed, the only fracture zone that can be followed from side to side across the Atlantic is the Arkhangelskiy (in the present-day nomenclature) fracture zone. As a result, we do not propose a major modification of the kinematic during the time interval when this fracture zone was tectonically active.

The main improvement in the kinematic models is based on the interpretation of what we call the Cretaceous-Jurassic Line (CJL), i.e. the boundary between the Cretaceous oceanic crust formed in the Equatorial Atlantic and the Jurassic oceanic crust previously formed in the Central Atlantic. We mapped the CJL west of the Demerara plateau as west of the Guinea plateau (Figure). The CJLs from both sides appear to be coincident before the formation of the Arkhangelskiy fracture zone, and formed a single structure that we interpret as a fracture zone related to a first stage of opening. It leads to two possible kinematic models that include a first stage of oceanic accretion in the Equatorial Atlantic probably during Aptian times.

The first way to interpret the CJL fracture zone is an improvement of the previously published models. It considers both West Africa and Northern South America as rigid blocks moving with the same kinematic in both the Equatorial and South Atlantic. This improved model results in a reasonable fit with the observed structures in both Equatorial and South Atlantic, although some discrepancies in displacement directions could not be resolved especially along the CJL.

To solve these discrepancies, we propose a second model that considers the geological observations (e.g. Soares Junior et al., 2011) suggesting two distinct rift propagations during the lower Cretaceous. A northern and slightly older rift propagation developed from the Central Atlantic towards South East to reach the present-day mouth of the Amazon River, and a southern rift propagated westward from the northern edge of the South Atlantic. Once these two rifts connected, the kinematic of the South Atlantic prevailed leading to a kinematic change between the Amazon mouth and the Central Atlantic. These two rifts can be accounted in a kinematic model assuming deformation within the South America plate, mainly between the Guyana shield and the northern Brazilian craton. Such intraplate deformation implies strike-slip in the eastern Amazonian basin, North-South shortening in the western Amazonian basin (as recorded by the Jurua orogen: Costa, 2002), and extension in the numerous lower Cretaceous basins of the northern Brazilian craton.

This kinematic model with two rift zones has important implications in the opening of the Equatorial Atlantic. It suggests the formation of an older than expected oceanic crust west of the Demerara plateau (and south of the Guinea plateau), and a two stages rift along the Cretaceous margins of these two plateaus, that may change the mapping of the last continental contacts and the incipient lower Cretaceous marine North-South connections.

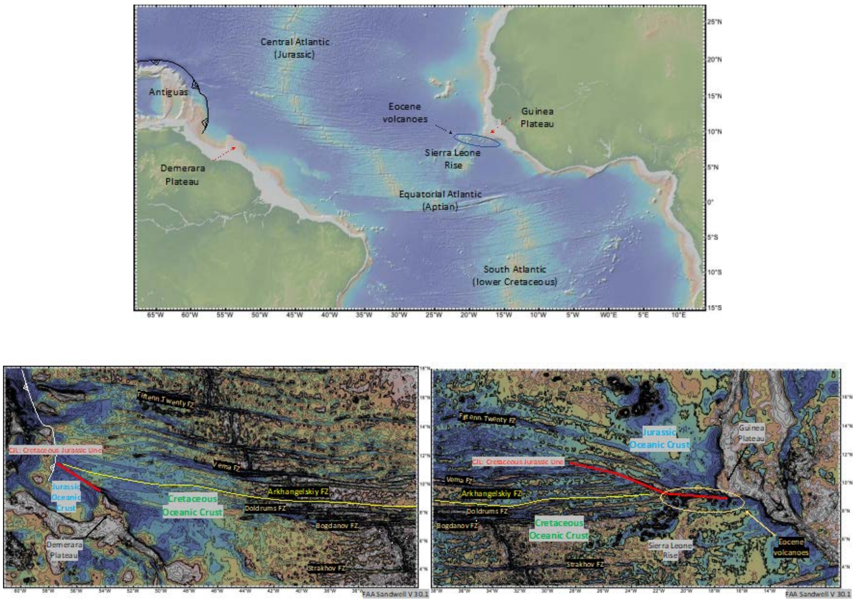

Figure: Geographic setting the of the Equatorial Atlantic, and fracture zones mapping in the northern Equatorial Atlantic (Free Air Anomaly map from Sandwell et al., V. 30.1)

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The opening and evolution of the Equatorial Atlantic Gateway: state of the art and future ocean drilling proposals

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The opening of the Equatorial Atlantic Gateway (EAG) during the breakup of West Gondwana (the separation of South America and Africa) was one of the most important tectonic events of the Mesozoic. The EAG resulted in a marine connection between the emerging ocean basins of the North Atlantic and South Atlantic, which led to fundamental changes in ocean circulation. The new bi-hemispheric Atlantic Ocean was critical to the long-term transition from the greenhouse-hothouse world of the Mesozoic to the late Cenozoic icehouse climate.

The opening of the EAG took place in several stages between the Early and Late Cretaceous along the oblique rift and transform margins of Africa and South America. However, the age of opening and deepening of the EAG remains poorly constrained, because of the limited amount of core data in the central Atlantic region and the fact that the opening took place during the Cretaceous Normal Superchron (CNS). The EAG remained restricted until sometime between the Aptian and Cenomanian, when a north-south connection was established and gradually deepened. This means that there remains a ~20 Myr uncertainty in the timing of onset of ocean spreading around the EAG, which in turn affects our ability to constrain subsidence rates and deep-water circulation patterns.

The last 'pinch-point' of this separation was along the transform margin of northwest South America and West Africa, between the Romanche/St Paul Fracture Zone in the south and Guinea Fracture Zone in the north. Separation of the two continents took place along a series of individual, oblique rift systems separated by transform (strike-slip) faults, now preserved as fracture zones that segment the conjugate margins of West Africa and South America. Transpression along these individual transform faults led to the development of isolated marine basins, which were eventually connected during the post transform tectonic stage, when the continents were fully separated. These individual rift basins and the marginal plateaus that form the southern and northern ends of the EAG contain a unique record of these events, including the timing and origin of marine inundation, as well as the subsequent evolution of the oceans at low latitudes. However, Mesozoic stratigraphic archives from these basins, and the Equatorial Atlantic in general, are very limited, with only ODP Leg 159 (Cote D'Ivoire) and Leg 209 (Demerara Plateau) recovering samples from the Albian or older strata.

We here present new seismic stratigraphic evidence from the north (Guinea Plateau) and south (Pernambuco Plateau), that allow us to add more constraints to the opening and deepening of this gateway through time. This provides us with a stratigraphic framework for a new set of ocean drilling proposals in the region, which aim to recover new continuous core records to reconstruct ocean conditions through this critical mid-Cretaceous time period. These proposals include expedition 388 to the Pernambuco Plateau and proposal 1004-APL in the Guinea Plateau. We will discuss these objectives, as well as a new drilling proposal in preparation in the West African margin.

Implication of Palinspatic reconstructions in the evolution of the central Mediterranean sills during the Messinian Salinity Crisis.

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Marine corridors represent important boundaries for the movement of water masses, biotopes and sediments over time. Either of sedimentary or geodynamic origin, marine gateways have constantly influenced the distribution of sedimentary and environmental environments through vertical movements or by sea level variations,. The Messinian Salinity Crisis (5.97-5.46 Ma) forms a unique milestone in the study of Mediterranean and Paratethysian gateways. However, past attempts at palaeogeographic and kinematic reconstructions in the Messinian have led to various models, often based on the present-day physiography of the Mediterranean area. Thus, the transition between western and eastern Mediterranean basins is often located at the level of the shallow Tunisian-Sicilian sill, along the Mesozoic Pelagian platform. The validity and underlying assumptions then require kinematic testing in the light of current geological and geophysical data.

The compilation of published information on the segmentation, geochronological composition of the crustal domains and the environmental evolution of the different domains, we present a palinspatic and palaeogeographic evolution of the central Mediterranean domain during the MSC. This model illustrates the importance of kinematic reconstructions in the history of past landscapes and marine gateways. By reconstructing the Ionian Sea much further west, this presentation aims to question the role of the Siculo-Calabrese gateway in the respective evolution of the sedimentary environments between the western and eastern domains in the Mediterranean during the different stages of the MSC.

Keywords: Mediterranean Sea, Messinian Salinity Crisis, Marine gateway, segmentation

Closure of the Central American Seaway: a Review

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Closure of the Central American Seway has been traditionally approached from an oceanographic point of view, using distal proxys to correlate changes in oceanographic variables (temperature, salinity, isotopic composition) with a very well dated event: the GABI (Great American Biotic Interchange). Three different kinds of closure, however, must be distinguished first: 1) Tectonic, 2) Geographic, and 3) Ecological. The first one, dictated by isostasy, suggests that once there is no normal oceanic crust separating the Pacific Ocean and the Caribbean sea, no 3-4 km ocean depths can be expected. The second one, geographic, results when continuous, or nearly continuous, land exists joining the continents via a land bridge, even if this bridge is discontinuous and allows shallow, ephemeral sea straits across. Lastly, ecological closure takes place when it makes sense for the organisms living on either side to cross-over the established bridge. Ecological closure can only take place the previous two (first tectonic, and then geographic) have already taken place. The abundant, and well-dated fossil record of the GABI relates to the last kind of closure: ecological, and likely dates a time when ecological conditions were such that faunal exchange became viable: a time when a cooler-drier climate expanded the savannas in northern South America, and allowed migrations. In the Central American Seaway closure, distal oceanographic proxies have traditionally been correlated (based on approximate simultaneity) with the changing ecological conditions on an already geographically closed Central American Seway. New data regarding ecological conditions in northern South America and southern Central America have emerged in recent years, suggesting that a change to drier conditions did indeed take place around the time of GABI. Additionally, new data has emerged regarding the paleodepth of late Miocene-Pliocene straits across the Isthmus, showing much shallower depths than previously thougth. Both data sets suggest that the Central American Seaway was already tectonically, and geographically closed by the time of the GABI. Additional mapping in the Isthmus of Panama is allowing refinements in the palegeographic configuration of this seaway.

Biogeographic Mechanisms Involved in The Colonization Of Madagascar By African Vertebrates: Rifting, Rafting And Runways

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Madagascar's vertebrate fauna shows a complex biogeographic pattern that confounds generalisations developed from other islands. For 80 years popular opinion has held that most of Madagascar's terrestrial vertebrate fauna arrived via transoceanic dispersal (i.e., by rafting or swimming), chiefly from Africa. The Ali-Huber model proposed a jet-like eastward Palaeogene currents which would allow animals to reach Madagascar in 3 – 4 weeks (through hibernation), whilst others like hippopotamuses are supposed to swim across the Mozambique Channel. We re-investigated the Ali-Huber model by tracking particle trajectories in currents simulated using the Institut Pierre-Simon Laplace Earth System Model, under similar palaeo-geographic constraints and showed that the model considerably underestimated the time required to cross the Mozambique Channel under simulated palaeogeographic conditions. Moreover, hibernation is probably an adaptation to Madagascar's hypervariable climate, and of doubtful value to waif mammalian colonists. In another hand, due to their limited aquatic abilities and their physiology, hippopotamuses would not have been capable of crossing the Mozambique Channel by swimming.
Thanks to the new and huge dataset collected during the PAMELA (Passive Margins Exploration Laboratories) research programme conducted in the Mozambique Channel by more than 100 researchers, which included eight oceanographic cruises (for a total of 224 days at sea) between 2014 and 2017, and three onshore geological surveys (for 50 land days) in 2017 and 2018, we have conducted an holistic, sedimentary, tectonic, kinematic, and palaeo-environmental study in this part of Indian Ocean.

We reported the existence of three short-lived land bridges between Africa and Madagascar at 66–60 Ma, 36–30 Ma and 12–05 Ma, thereby concluding that Madagascar's extant biota was likely built up with the contribution of fauna dispersed following the three Cenozoic land bridges rather than through transoceanic rafting or swimming, although vicariance, island hopping and limited rafting also possibly played a role (Masters et al., 202, 2022; Pellen et al, 2022). We then test the proposal of that episodic land bridges by comparing divergence estimates of Madagascar’s angiosperm taxa with their dispersal mechanisms (Génin et al., 2022).

The early Oligocene to early Pliocene material from Site DSDP 242 can be considered the first important contribution to more comprehensive understanding of the characteristics of the series of land bridge connections across the Mozambique Channel. The preliminary palynological results provides a new promising avenue to document the occurrence of periodic land bridge connections between the African mainland and Madagascar.
Because the presence of these land bridges limits inter-basin exchanges of the ocean water masses and radically modifies the parameters used for palaeocurrent modelling, these modifications are presently analysed using coupled global simulations at low resolution (2°) at the LSCE and regional oceanographic models at higher resolution (1/12°). The impacts of possible oceanographic modifications will be tested against changes in the sediment architecture inferred from seismic data as well as from Foraminifera, most sensitive to changes in salinity and temperature, studied from borehole sediments.

Keywords : Endemism, Segmentation, Land Bridge, Madagascar, Geodispersa, Vertical motion, Co-evolution, pollen, Paleocurrent

Two: Oceanographic, Palaeoceanographic and Sedimentary processes and deposits

Keynote - Ricardo F. Sánchez-Leal

Water masses circulation and oceanographic processes on Gateways: the study case of the Strait of Gibraltar

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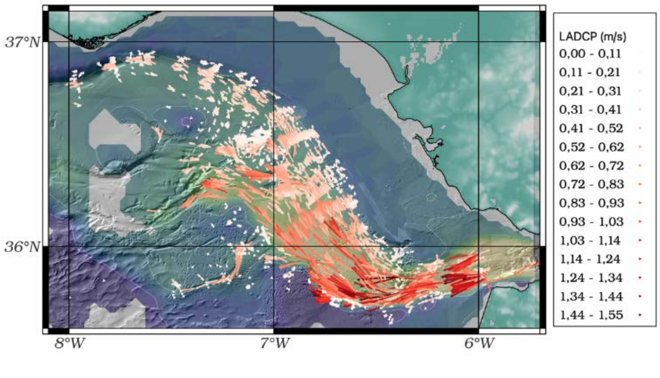
The pathways and transformations of dense water overflows are a central piece in the ocean's large-scale circulation. These depend on small-scale interactions between the flow and the seabottom. In this paper we present a novel, high-resolution current and hydrographic data set and highlight the intricate pathway travelled by the saline Mediterranean Overflow as it enters the Atlantic. We focus on how the interaction with the topography triggers a number of very interesting processes that model the current spreading. Over the initial 200 km west of the Gibraltar gateway, distinct channels separate the initial gravity current into several plunging branches depth-sorted by density. Shallow branches follow the upper slope and eventually detach as buoyant plumes. Deeper branches occupy mid slope channels and coalesce upon reaching a diapiric ridge. A still deeper branch, guided by a lower channel wall marked by transverse furrows, experiences small-scale overflows which travel downslope to settle at mid-depths. The Mediterranean salt flux enters the Atlantic at different depth levels. Since this flux has implications for the buoyancy balance in the North Atlantic, its quantification is key to accurately measuring and understanding the role of Mediterranean Outflow in past, present and future climate scenarios.



Gulf of Cádiz (SW Iberian Peninsula). Near-bottom lowered-ADCP velocity vectors (meters per second) over sea-bottom salinity contours (lighter shades outline the pathway of the Mediterranean Outflow) and swath bathymetry relief.

Contourite processes associated with the overflow of Pacific Deep Water within the Luzon Trough: conceptual and regional implications

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Overflows through oceanic gateways govern the exchange of water masses in the world’s ocean basins. These exchanges also involve energy, salinity, nutrients, and carbon. As such, the physical features that control overflows can exert a strong influence on regional and global climate. Here, we present the first description of sedimentary processes generated by the overflow of Pacific Deep Water (OPDW) (Figure 1). This mass flows southward at approximately 2000–3450 m water depth within the Luzon Trough (gateway) from the Pacific Ocean into the South China Sea. OPDW can be divided into: a) a lower, denser layer (including an associated weak counter- current), which has generated a large contourite depositional system (CDS-1) that includes large erosional (channel and moat), depositional (mounded and plastered drift), and mixed (terrace) contourite features along the trough bottom and walls, and b) an upper mixing layer, which has not generated any significant depositional or erosional contourite features. Where OPDW does not reach the seafloor, it is underlain by bottom water that circulates more sluggishly but has generated a second contourite depositional system (CDS-2) made of a large sheet-like drift. The OPDW flow has generally enhanced since the middle to late Miocene, except in the shallower northernmost corridor. In the deeper main trough, reductions in width and depth of the gateway by Taiwan orogenic events have likely accelerated the overflow. The latest significant enhancening may promote wide- spread development of contourite depositional systems along the South China Sea’s lower continental slope and adjacent deeper areas. This work highlights the importance of gateway-confined overflows in controlling the morphology and sedimentary evolution of adjacent deep marine sedimentary systems. A clear understanding of overflow processes and their products is essential for decoding tectonic control in oceanographic or pale-oceanographic processes.

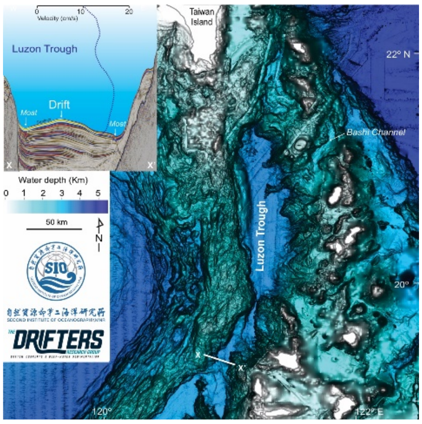

Figure 1 Multibeam bathymetry of the Luzon Trough, as well as a seismic reflection profile across the middle trough, showing the modern contourite features.

Sea level control sedimentary evolution of the Taiwan Strait

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Straits are one of the most dynamic settings where marine deposits accumulate. Existing literature has established the model for tidal straits, in which sedimentation is dominated by tidal currents. Besides tidal currents, many different processes (e.g., mass-transport processes, waves and ocean currents etc.) can operate within an individual strait. However, there are far too few studies of the sediments in straits to reveal sedimentary processes. Taiwan Strait connects a wide, shallow marginal sea and the deep South China Sea. A branch of the Kuroshio Current flows northward through Taiwan Strait and generates the high-temperature, high-salinity Taiwan Warm Current. A possible contourite drift is present in the center of the shallow Taiwan Strait, where it is supplied with sediment transported offshore from the island of Taiwan and carried by the Taiwan Warm Current. The Changjiang-derived sediments, in addition to being deposited in the Changjiang delta, were mostly carried southward by the low temperature, low salinity and high suspended-sediment concentration Zhejiang-Fujian Coastal Current, and can extend into the Taiwan Strait. Strait-margin deltas are actively exporting sediment from Taiwan into Taiwan Strait through hyperpycnal flows. Modern observation suggests that the waves and tides were strong in the strait, which presumably rework strait sediments.

To investigate the sedimentary evolution of the Taiwan Strait, we used Chirp shallow seismic stratigraphy and ^{14}C dating of two sediment core (30 m long each) from the Strait to provide a regional stratigraphic framework. We also use process-oriented sedimentology, coupled with provenance analysis and organic geochemistry of sedimentary records of the Taiwan Strait to reveal sedimentary processes. The clay mineralogy and U–Pb detrital zircon geochronology were analyzed to determine the provenance evolution. Based on comparing the depositional ages of the various sedimentary units with the global eustatic sea-level curve, the evolution of water depths was reconstructed. The results indicate the following.

(1) Four regional unconformities were identified in the seismic sections that probably correspond to the Last Glacial Maximum, MIS 4, MIS 6 and MIS 8. The LGM sequence boundary shows pronounced erosion at the southern strait, because the rivers from Taiwan Island occupied in the strait at this time. The MIS4 valleys in southern strait were likely incised by the rivers from the Taiwan Island, whereas the MIS 4 valleys from northern strait were probably created by the Taiwan rivers.

(2) ^{14}C ages reveal that the fill of the MIS 4 valleys accumulated during MIS 3. Both two cores have revealed the presence of Changjiang mud in Taiwan Strait during MIS 3. This implies southward transport of the Changjiang mud by the Chinese coastal current during MIS3. This is the first time that the existence of the Changjiang Coastal Mud Belt during MIS 3 is documented. Integrated water-depth estimates, provenance and core observations reveal the presence of distinct shallower-water and deeper-water facies within the Changjiang Coastal Mud Belt. The shallower-water (<20 m water depth) facies contain fluid-mud layers, highlighting the role of waves and tides in resuspending previously deposited muds. The deeper-water facies (20–60 m water depth) contain muds that were influenced by ocean currents and are more intensely bioturbated and commonly enriched in shell material. The facies distribution documented here may be useful for the identification of other paleo-CMB deposits.

(3) The several internal truncational surfaces within the central mound in the Taiwan Strait recorded shifts in the sites of deposition/erosion, which presumably are the result of changes in the flow paths of the various currents that pass through the Strait. The location of strong

reflections in the seismic profiles reflect the interaction between storm waves and contourites.

New data on sedimentary processes in the Charlie-Gibbs Fracture Zone area during the Late Pleistocene to Holocene

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The Charlie-Gibbs Fracture Zone in the North Atlantic is a mega-transform system in the Mid-Atlantic Ridges which represents the deep oceanic gateway that connects the Iceland and West European Basins with the Irminger Basin. At present, the Charlie-Gibbs serves as a deep-water corridor for the Iceland-Scotland Overflow Water (ISOW) which is part of the lower limb of the ocean conveyor belt that affects the global climate. The ISOW-related contour current, which is channelized in fracture valleys, influences the sedimentary processes that produce contouritic drifts, whose sediments may serve for high-resolution paleo-reconstructions. The aim of this study is to determine the sedimentary processes in the area of a tectonically active deep-water gateway and to reconstruct the climatic and bottom current variability as reflected in the sediments.

New geological and geophysical data in the area of the Charlie-Gibbs Fracture Zone were obtained during the cruises of R/V Akademik Nikolaj Strakhov (2020) and R/V Akademik

Sergey Vavilov (2021). The surveys included: bathymetric studies using the RESON Seabat-7150 deepwater multibeam sonar system, profiling of the topmost part of the sedimentary cover with an EdgeTech 3300 profiler (2-6 kHz), retrieval of two sediment cores using a gravity corer.

Analysis of the acoustic profiling data revealed four Quaternary seismic complexes. We assume that the formation of these complexes is related to glacial cycles, which control the supply of terrigenous material from the nearby continental areas by ice/iceberg rafting. Sedimentary bodies in the form of seismic facies draping structural features were recognized in the abyssal zone adjacent to the study area from the northeast and along fault troughs. These seem to be formed mainly by contour currents which construct mounded, elongated and channel-related contourite drifts. There are numerous sedimentary bodies with a chaotic internal structure and a higher degree of acoustic turbidity in the fracture zone area. They accumulated as a result of sediment gravity flow processes which are widespread seismically active regions. The registered deviation of acoustic stratification from the sub-horizontal bedding is proposed to be due to a combination of two factors: the enveloping of basement heterogeneities with sedimentary material and also tectonic deformations. Areas with amplified reflections in the sediment between folded and piercement structures indicate an admixture of volcanoclastic material. The sediment-filled fault troughs show signs of neo-tectonic dislocations in the sediments in both the active and passive parts of the fracture zone.

The sediment cores ASV-5308-C1 (52°37.080’ N 33°34.726’ W, 4.65 mbsf, 3850 mbsl) and ASV-5309-C2 (53°03.301 N 33°32.719 W, 5.20 mbsf, 3140 mbsl) were retrieved from the southern slope plateau in the northern valley of the active part of the fault and from the confined basin in the southern part of the Reykjanes Ridge, respectively. The cores were studied with a variety of analyses including magnetic susceptibility (MS), X-ray fluorescence, ice-rafted debris (IRD) and foraminiferal counts, $CaCO_3$ and total organic carbon analyses. Smear slide examination, X-ray diffraction, and grain-size analyses are going to be performed for the sediment description and reconstruction of sedimentary regimes in the study area.

Four sedimentary facies have been defined based on the preliminary analysis of available data. The cores are characterized by two similar facies. The upper parts of ASV-5308-C1 and ASV-5309-C2 cores (0–280 cm and 0–340 cm, respectively) consist of clayey silts with increasing carbonate concentration to the top of the core (from 20 to 70%), low IRD, and planktonic foraminifera *Neogloboquadrina pachyderma* (sin.) content. These features together with small concentrations of terrigenous elements (Fe, Zr, Rb, Ti, and Sr), low MS, and numerous signs of bioturbation lead us to interpret the sediment as silty contourites of Holocene age accumulated under the influence of paleo-ISOW bottom current. The lower parts of both cores consist of sandy silts with variable (ASV-5308-C1) and low (ASV-5309-C2) $CaCO_3$ content, high IRD and *N. pachyderma* (sin.) values, and increased concentration of terrigenous elements. Bioturbation is also typical. This facies is interpreted as being hemipelagic and related to the glacial Late Pleistocene interval which was characterized by weakening of the paleo-ISOW flow and increasing terrigenous material (IRD) supply from the nearby continental areas.

The prominent feature of the recovered sediment is the specific sedimentary facies in each core. In the ASV-5308-C1 at 336–375 cm, there is a sediment layer which is characterized by a minimum in $CaCO_3$, IRD, and foraminifera content. Simultaneously, very high MS values (up to 30 times higher than background) and a jump in Ti, Fe, and Zr values were registered, pointing to the high titanomagnetite content. In the lower part of this interval, prominent bedding was recognized. The nature of the facies is still unclear unclear and further studies are needed.

In ASV-5309-C2, a diatom mat was registered at 340–370 cm. Low values of both biogenic calcareous and terrigenous components are common for this layer. The diatom mat may be linked to strong changes in surface water productivity related to the Subarctic Front position as shown by earlier studies.

In summary, the combination of geomorphological and sediment composition studies enables us to update the existing understanding of sedimentary processes in the Charlie-Gibbs Fracture Zone. The contour currents amplified by the narrow valleys of the fracture zone played an important role in sedimentation during the Holocene. The influence of terrigenous material input during the glacial interval and the proximity of the Subarctic Front to the study area during the Pleistocene to Holocene transition were also registered.

The study was supported by the RSF, grant No.22-17-00170.

Paleoceanographic setting and depositional processes in the Discovery Gap (Azores—Gibraltar Fracture Zone, NE Atlantic)

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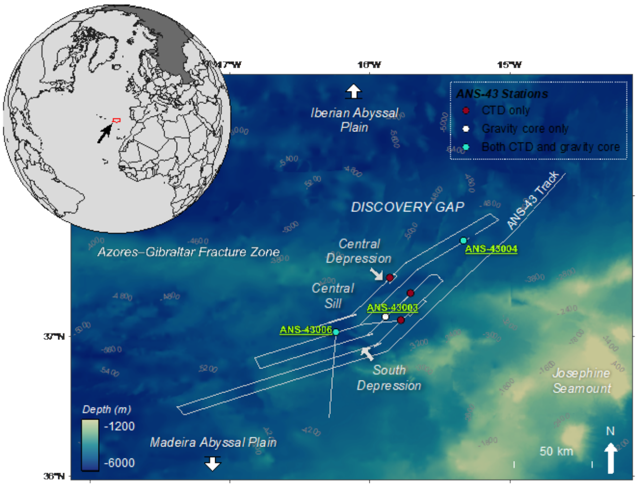
The low current velocities and low sediment accumulation rates often associated with abyssal plains can make identifying bottom current influence challenging. Such influence may be limited to condensation and non-deposition of sediment, but erosion may also occur if currents are particularly intense. However, the changes in current velocity through deep marine gaps connecting adjacent abyssal plains may be sufficient to increase sediment deposition or erosion. Therefore, sediments in deep marine gaps and gateways have the potential to provide insight into the palaeoceanographic conditions in abyssal environments.

To better understand how bottom current influence is exhibited in such sediments, we undertook a multi-scale study of Discovery Gap, a deep marine gap connecting the Iberian and Madeira abyssal plains through the Azores–Gibraltar Fracture Zone (Fig. 1), with data collected on the R/V *Akademik Nikolaj Strakhov* in 2019. Three sedimentary cores, along with hydrological and geophysical (high resolution seismic and bathymetry; Fig. 1) data were collected to determine the distribution of water masses with regards to morphological and sedimentary features.

Figure 1. An overview of the study area with the location of the three sedimentary cores indicated.



All three cores show repeating vertical variation from light to dark sediment with corresponding changes in grainsize and geochemistry. However, core ANS-43006 from the deepest part of the gap (5275 m; Fig. 1), shows laminations and mud-ripples within these dark, carbonate-poor layers. Isotope analysis reveals that in all the cores, these darker units are closely associated with the cool Marine Isotope Stages (MIS 6, 4 and 2), although the sedimentary structures in ANS-43006 only appear in the mid- to late glacial stage. We interpret these laminations and ripples to be indicators of bottom-current reworking associated with the Antarctic Bottom Water which is present at these depths in Discovery Gap. These laminations may be a sign of increasing velocities where there is no supply of coarse material to the sea floor to create coarser-grained deposits.

The presence of these sedimentary structures in the center of the gap, compared to their absence north of the gap, is a sign of reduced influence of the current as it exits the gap. This is in agreement with the proposed pathways for present-day AABW in the gap. While

NE–SW trending highs north of the gap do control the currents and intensify erosion and deposition, as evidenced by the presence of moats and drifts, the majority of the current is being deflected by E–W trending highs within the gap, causing it to slow down and even recirculate in the deep central depression (Fig. 1).

To determine whether the observed sedimentary structures can be reliably attributed to heightened bottom current activity, further work is required to map the distribution of this laminated facies relative to bottom current pathways particularly in other deep marine gaps and gateways.

This work was completed within the framework of "The Drifters" Research Group at Royal Holloway, University of London (RHUL) with funding through the IO RAS state assignment no. FMWE-2021-0012.

Keynote - Heiko Hüneke

Sedimentary processes and deposits associated to Gateways: a perspective from the ancient sedimentary record

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Contourites (bottom-current deposits) are widespread in deep-marine environments of our modern icehouse world, but have also been formed during greenhouse conditions, such as the Devonian period, typically in association with oceanic gateways. The examples from the ancient record can help establish better diagnostic criteria for differentiating them from other deep-sea deposits and enhance our understanding of how they may record past global oceanic circulation, tectonic events, and gateway evolution.

The Devonian case reveals bioclastic carbonate contourites preserved in the Harz (Germany), the Carnic Alps (Austria), the Moroccan Meseta, the High Atlas, and the Tafilalt (Morocco). Contourites occur in the early Emsian and Eifelian-Famennian periods interstratified with pelagic/hemipelagic sediments and locally gravity-flow deposits. The contourite facies builds up strongly condensed and reduced successions with stratigraphic gaps, which also occur with similar features in deep-marine records of the same age in other areas of southern Europe and northwest Africa. The studied locations exemplify different plate tectonic settings and palaeogeographic domains within a low-latitudinal, east-west trending, deep-marine realm (Prototethys, Paleotethys, Rheic, Rhenohercynian Ocean), located between Gondwana in the south and Laurussia in the north, and including a set of continental terranes (Armorica, Galatia, Hanseatic). Multidisciplinary approaches were used to discriminate contourite facies associations, to propose a sedimentary model, to interpret the relations with the narrowing of the seaways between Gondwana and Laurussia, and to identify links with Devonian oceanic anoxic events and evolutionary crisis.

The identified bioclastic contourites represent bi-gradational sequences that normally form in association with contouritic drifts, frequently having partial-sequence characteristics of plastered drifts and contourite terraces. The coarser (calcarenitic) contourites, formed during the early Frasnian, are locally associated with biostratigraphic gaps and phosphate deposits, indicating an alternation between depositional and erosional conditions, driven primarily by energetic bottom currents. This simultaneous intensification of palaeocirculation at different locations during the Frasnian was likely caused by a gradual narrowing of the oceanic gateways between the continental plates of Gondwana and Laurussia and the intermediate terranes.

The sedimentary model proposed for the Tafilalt Platform in Morocco is based on bed- and drift-scale contourite features, which reflect pelagic sedimentation and deposition from bottom currents on a contourite terrace, a gently inclined section of the upper slope of Gondwana shaped by a water-mass interface: (i) Oxic clear-water currents produced bigradational contourite sequences including thin coquinas of planktic and nektic organisms and minor hiatuses (erosional surfaces, hardgrounds) at the midpoint of these incomplete sequences, which are frequently associated with hiatal lag concentrations of carbonate intraclasts, ferromanganese nodules, conodonts and quartz grains. (ii) Contourites deposited from a dysoxic-anoxic water mass comprise thick coquina beds of planktic and nektic organisms, which show well-preserved traction structures (parallel- and cross-lamination) due to absent or sparse bioturbation and are in many cases bounded by biostratigraphic gaps. (iii) Current-reworked crinoid meadows gave way to predominant complete contourite sequences and rare ferromanganese encrustations on skeletal grains and hiatuses. (iv) Hiatal lag deposits indicative of energetic bottom currents preserve concentrations of carbonate intraclasts, ferromanganese nodules, large goniatite shells and conodonts, which typically drape hardgrounds and erosional surfaces.

Biostratigraphic data and the overall depositional architecture documented for the Tafilalt Platform display palaeoceanographic hydrodynamic processes associated with a shifting water-mass interface. The inner terrace was characterized by an alongslope contourite channel and a small mounded drift at its downslope margin. On the outer terrace, energetic bottom currents caused abraded surfaces, i.e. plain areas of non-deposition and localized erosion, and sandy condensation layers. The microfacies reflects repeated alternation between suspension deposition, winnowing of fines, bedload traction, dynamic sediment bypassing, together with concomitant seafloor cementation and sedimentary reworking, which prevented accumulation over long periods (longer than a biozone).

This study demonstrates the role of oceanic gateways in controlling the paleo-circulation during global greenhouse conditions that, in turn, controlled contourite depositional and erosional processes and shaped the morphology of the continental margins. It also provides clues linking the paleo-circulation to the numerous oceanic anoxic events, some of which appear global in scale and coincide with Devonian biotic crises. The interpretation is complicated by palaeocirculation models that are conflicting in many regards, not least because of the contradicting published plate-tectonic and palaeogeographic reconstructions of the Devonian earth. In particular the extent of the oceanic domain between Gondwana and Laurussia is somewhat controversial, especially the palaeolatitude of the northwestern margin of Gondwana and its geographical relation to eastern North America and the terrain assemblage of southern Europe.

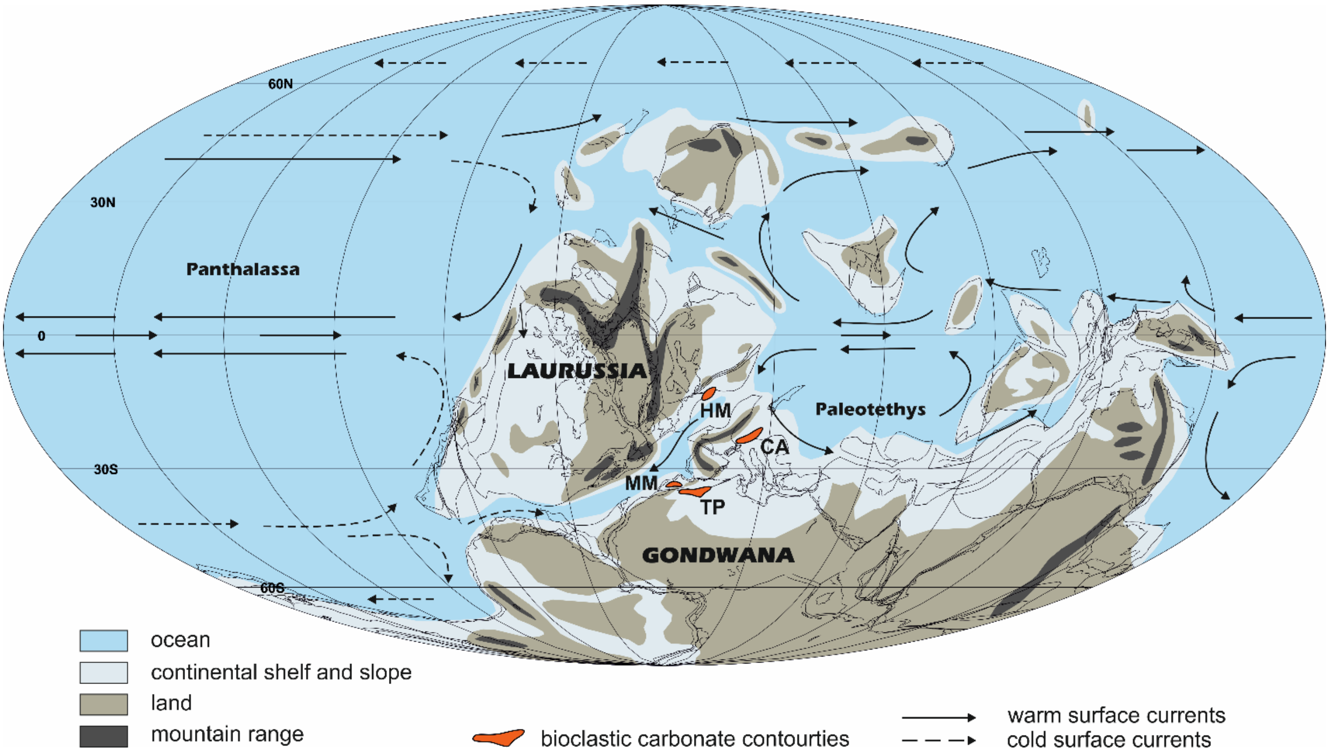

Figure 1. Palaeogeographic reconstruction of the earth during the Givetian–Frasnian transition (370 Ma) showing expected pattern of oceanic surface circulation and distribution of carbonate contourties associated with deep-marine gateways between Gondwana and Laurussia (modified from Hüneke, 2006). Map provided by Wolfgang Kiessling (Copper, 2002), based on reconstruction of Golonka (2002). HM – Harz Mountians, CA – Carnic Alps, MM – Moroccan Meseta, TP – Tafilalt Platform.

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Mixed carbonate-siliciclastic contourite drift deposits associated with the entrance of an Atlantic-Mediterranean corridor (late Miocene, southwest Spain)

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Carbonate contourite drifts are poorly documented in the fossil record, onshore, because of the difficulty of implementing diagnostic criteria for their recognition. Accordingly, little is known about the relative position of carbonate drifts with respect to ancient carbonate platforms, seaways and shallow passages within the context of palaeoceanography. This study presents a fossil example of mixed carbonate-siliciclastic drift cropping out in a quarry in Osuna (Sevilla province, southern Spain) at the northern end of the Guadalhorce Corridor, a Miocene strait connecting the Mediterranean Sea and the Atlantic Ocean in the Betic Cordillera (Fig. 1).

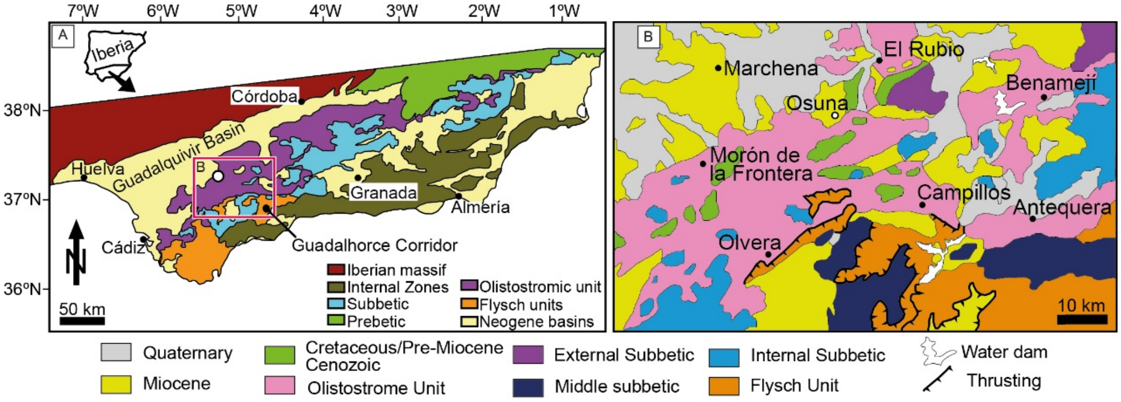

Figure 1: *Geological setting. A) Location of the study area in South Spain. Red frame indicates the position of Fig. 1B as well as the location of the Guadalhorce Corridor and the Osuna Quarry section (white dot). B) Close up of the different geological units cropping out in the surroundings of Osuna (37º 14' N, 5º 06' W).*

Based on the facies and sedimentary structures, the studied succession is divided into three units (Fig. 2): 1) the lower unit, Unit 1, is a 33-m thick succession of large carbonate bodies with mega cross-stratification pointing to the southeast and secondarily to the northwest interpreted as a contourite drift; 2) the intermediate Unit 2 is a 0.5 - 2-m thick terrigenous conglomerate body eroding the top of Unit 1; and 3) the uppermost Unit 3 consists of a 6-m thick siliciclastic-dominated succession with herringbone cross-stratification and a dominant direction of the structures to the northwest interpreted as tidal deposits.

Unit 1 can be interpreted as a contourite drift deposit due to the occurrence of: 1) up to 10-m thick sediment bodies with planar or through mega cross-bedding; 2) two dominant directions of the sedimentary structures; and 3) reactivation surfaces usually marked by changes in the grain size of the sediment. The two flow directions recorded by the sedimentary structures (Fig. 2) are related to the position of the contourite drift at the northern end of the coeval Guadalhorce Corridor. The dominance of sedimentary structures pointing to the southeast is the result of the Atlantic inflow into the Mediterranean, while the structures oriented to the northwest record the Mediterranean outflow through the corridor. The dominance of either inflow or outflow waters through the strait was likely modulated by relative sea-level fluctuations.

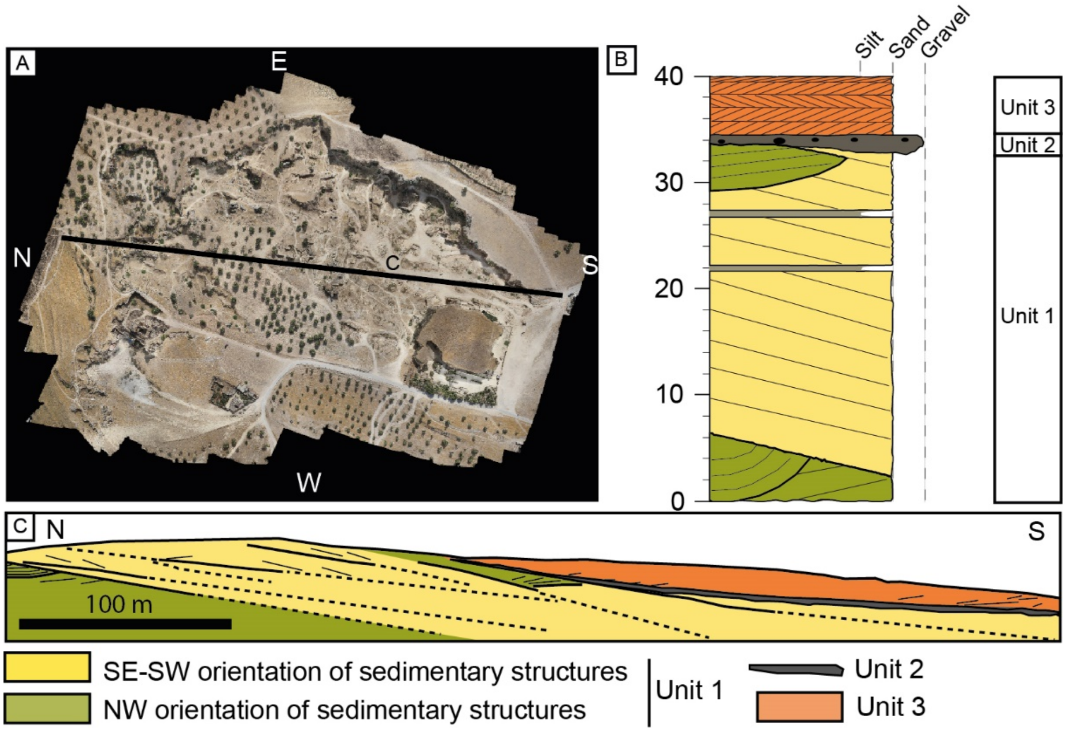

Figure 2: *Osuna Quarry. A) Top view of the photogrammetric model. B) Stratigraphic profile of the Osuna Quarry section with the location of the micropalaeontology samples. C) Cross-section of the Osuna Quarry showing the geometry of the different units and the orientation of the sedimentary structures. Solid thick lines represent surfaces separating large sediment bodies traced on a photogrammetric model. Dashed lines are the likely continuation of those surfaces. Thinner lines represent the internal structures inside the sediment bodies.*

The conglomerate of Unit 2 suggests regional uplift of the southern margin of the Guadalquivir Basin that promoted a turnover in the depositional mode from a bottom-current dominated (Unit 1) to a tide-dominated environment (Unit 3). This tectonic pulse recorded by the increase in the amount and grain size of siliciclastics was likely related to the closure of the Guadalhorce Corridor.

The Osuna Drift indicates for the first time the occurrence of bottom currents related to the Atlantic inflow through the Betic Cordillera during the Messinian which so far were only reported to occur through the Rifian Corridors. This also contradicts the classical “Siphon” model for the Atlantic-Mediterranean bottom-current circulation pattern during the Messinian and sheds light on the complex palaeoceanography during the Late Miocene that predates the Messinian salinity crisis.

Mixed carbonate–siliciclastic tidal sedimentation in the Mediterranean-Atlantic connection through the Zagra Strait (Betic Cordillera)

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The Zagra Strait developed in the early Tortonian as a narrow structurally-controlled marine corridor at the transition from the northwestern margin of the Mediterranean-linked Granada Basin to the Atlantic Ocean-linked Guadalquivir Basin during an important uplift period of the cordillera (Fig. 1). Its mixed carbonate-siliciclastic deposits record the effect of tidal current amplification and the key role of antecedent topography in sediment distribution. We document the sedimentological features of the Zagra Strait deposits and their spatial and temporal distribution in six sections at well-exposed outcrops, interpreting its sedimentary dynamics within the context of existing strait facies models. Our reconstruction of the Zagra Strait (Fig. 1) and age constraints improve the palaeogeographic reconstructions of the Atlantic-Mediterranean Betic connections during the Miocene. Large-scale (>10 m high) submarine dunes formed by superimposed, mostly 3D bedforms moved parallel to the strait margins under the influence of strong tidal currents. Dune distribution can be divided into three sectors with different palaeocurrent migration, lithological and topographical characteristics. In the northern sector, dune migration was at first dominated by southward-directed flood tidal currents. Southward migrating dune fields built a prograding cross-strata sand body into a deep (75-300 m water depth based on estimations from dune height) depression that separated the northern and central sectors, where tidal currents were weaker and dunes were not generated. In the central sector, dunes moved towards the north, also stopping at the depression boundary. The southern sector records a relative decrease in current strength compared with the northern and central sectors, and a significant increase in the bioclastic content in the sediment. Terrigenous content generally increases towards the strait margins, and reciprocally, carbonates towards its axis. Tectonic activity during deposition is evidenced by syn-sedimentary normal faults, sand injectites, fallen blocks engulfed between undeformed cross beds and soft-sediment deformation in the entire thickness of large-scale dunes, whose origin could also be linked to overloading processes. The closure of the Zagra Strait resulted from the progressive tectonic uplift of that part of the Betic Cordillera before the late Tortonian. The record of the strait closure was evidenced by the suppression of tidal influence in the nearby Granada Basin in the late Tortonian.

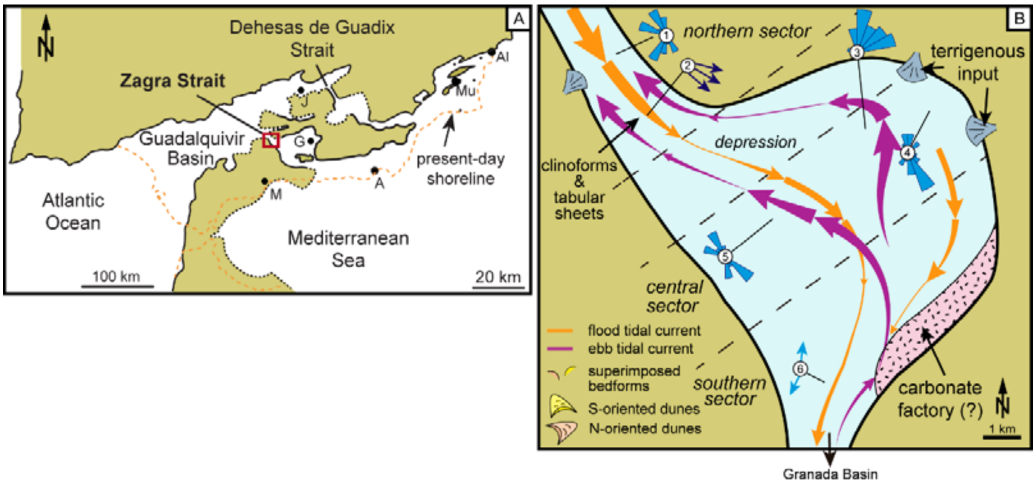

Figure 1. A) Early Tortonian palaeogeography of the Betic Cordillera after the closure of the North-Betic. B) Sketch illustrating the reconstruction of the Zagra Strait based on preserved outcrops.

Closing of the Betic-Rif corridors: considerations from the Late Miocene evolution of the Gulf of Cadiz

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The opening and closing of oceanic gateways strongly influence the global circulation and climatic conditions. The closure of multiple seaways during the Miocene and Pliocene led to the end of the global equatorial circulation and eventually established the modern circulation system, where the Betic and Rifian corridors were among them. The Late Miocene evolution of the Atlantic-Mediterranean exchange included the development of contourite depositional systems within these corridors, currently locate onshore southern Spain and northern Morocco, as well as downdrift in the Gulf of Cadiz. However, as the outcropping sedimentary records of these ancient marine corridors are incomplete due to syn- and post-depositional unconformities, the Gulf of Cadiz provides the ideal setting to unravel the nature and timing of the Atlantic-Mediterranean exchange during the Late Miocene.

Seismic stratigraphic analysis of the foreland basin system of the Southwestern Iberian and Northwestern Morocco margins generally consists of a four-stage contourite depositional system, located above the Gulf of Cadiz accretionary wedge. They include the initial-drift, growth-drift, maintenance-drift, and buried-drift stages, which are linked to bottom currents originating from the Rifian corridor and are observed mainly in the Doñana, Sanlucar, Cadiz and Offshore Gharb wedge-top basins. The initial-drift stage consists of sheeted drifts associated to weak bottom currents, which developed simultaneous to the emplacement of the allochthonous unit of the Gulf of Cadiz in an early convergent stage of the foreland basin system during the middle to late Tortonian. Coevally in the Deep Algarve foredeep basin, mounded to plastered drifts are identified locally due to the stronger bottom currents sourced from the Betic corridor. The growth-drift stage consists of mounded drifts associated to stronger bottom currents arising from sea-floor irregularities and the creation of accommodation, due to the influence of tectonic activity in a late convergent stage of a foreland basin system. During this stage, the lack of contourite drifts in the Deep Algarve foredeep basin is due to the restriction of the Betic corridor and isolation of the basin from structural highs. The maintenance-drift stage consists of more pronounced mounded drifts, or plastered drifts in shallower levels of the wedge-top basins, associated to vigorous bottom current activity, which also saw its influence advancing into the Deep Algarve foredeep basin, since the early Messinian. This transition from growth-drift to maintenance-drift stage is also regarded as the initiation of the stepwise-restriction of the Atlantic-Mediterranean exchange. The buried-drift stage consists of a dominantly pelagic or hemipelagic interval which indicates a cessation of the bottom currents in the Gulf of Cadiz and the fossilization of the Late Miocene contourite drifts, due to restriction of the bottom water exchange through the gateways since the middle to late Messinian. Whereas in the Deep Algarve foredeep basin, the Guadalquivir Sands turbidite system dominate the sedimentary record during this period.

This work demonstrates the interplay of bottom currents from complex oceanic gateway configurations in an active tectonic setting, which controls the local development of contourite deposits and their morphology, and how they are linked to the gateway restriction. It also allows for the understanding of the diagnostic criteria for contourites in active tectonic settings. More detailed studies involving the analysis of sediments through drilling of the geological record could help resolve the uncertainties related to the evolution of the Late Miocene contourite depositional system and the Atlantic-Mediterranean exchange, such as the upcoming IMMAGE (IODP895 & ICDP) and ALGEMAR projects.

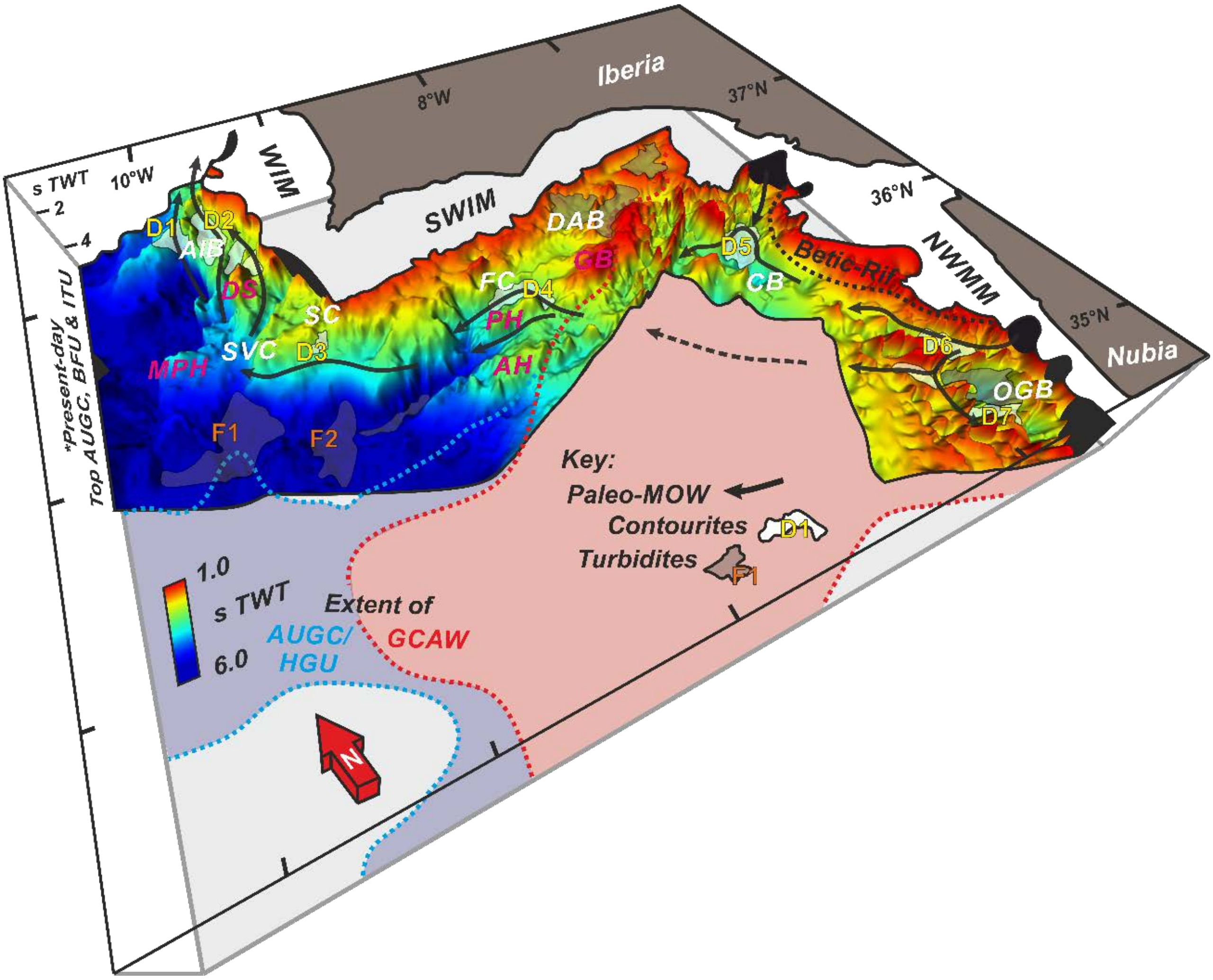

Figure 1. Schematic model for the relationship between contourite distribution (D1-D7) and potential pathway of the paleo-Mediterranean Outflow Water (MOW) for the Late Miocene Gulf of Cadiz CDS, superposed on a loosely represented paleobathymetry of the Late Miocene. (NWMM: Northwest Moroccan margin, SWIM: Southwest Iberian margin, WIM: West Iberian margin) (Ng et al., 2021).

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Investigating Miocene Mediterranean-Atlantic Gateway Exchange (IMMAGE): an amphibious drilling project

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Marine gateways play a critical role in the exchange of water, heat, salt and nutrients between oceans and seas. The advection of dense waters helps drive global thermohaline circulation and, since the ocean is the largest of the rapidly exchanging CO_2 reservoirs, this advection also affects atmospheric carbon concentration. Changes in gateway geometry can therefore significantly alter both the pattern of global ocean circulation and associated heat transport and climate, as well as having a profound local impact.

Today, the volume of dense water supplied by Atlantic-Mediterranean exchange through the Gibraltar Strait is amongst the largest in the global ocean. For the past five million years this overflow has generated a saline plume at intermediate depths in the Atlantic that deposits distinctive contouritic sediments in the Gulf of Cadiz and contributes to the formation of North Atlantic Deep Water. This single gateway configuration only developed in the early Pliocene, however. During the Miocene, a wide, open seaway linking the Mediterranean and Atlantic evolved into two narrow corridors: one in northern Morocco; the other in southern Spain. Formation of these corridors permitted Mediterranean salinity to rise and a new, distinct, dense water mass to form and overspill into the Atlantic for the first time. Further restriction and closure of these connections resulted in extreme salinity fluctuations in the Mediterranean, leading to the formation of the Messinian Salinity Crisis salt giant with knock on consequences for ocean chemistry and the global carbon cycle.

IMMAGE is an amphibious drilling project designed to recover a complete record of Atlantic-Mediterranean exchange from its Late Miocene inception to its current configuration. This will be achieved by targeting Miocene offshore sediments on either side of the Gibraltar Strait (Fig. 1) with IODP (Integrated Ocean Discovery Program) and recovering Miocene core from the two precursor connections now exposed on land in southern Spain and northern Morocco with ICDP (International Continental Drilling Programme). IMMAGE's IODP drilling has been scheduled between December 2023-February 2024 as Expedition 401.

The scientific aims of IMMAGE are:

- to constrain quantitatively the consequences for ocean circulation and global climate of the inception of Atlantic-Mediterranean exchange;
- to explore the mechanisms for high amplitude environmental change in marginal marine systems; and
- to test physical oceanographic hypotheses for extreme high-density overflow dynamics that do not exist in the world today on this scale.

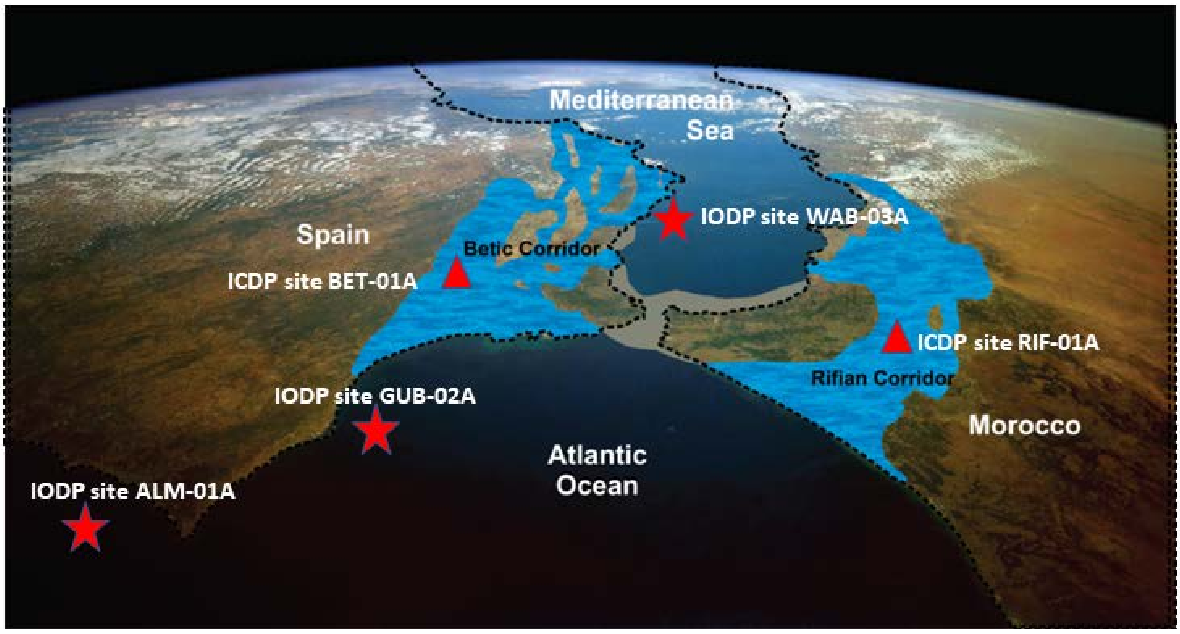

Figure 1. Map of the Mediterranean-Atlantic gateway at Gibraltar and the two Miocene connections, the Betic and Rifian corridors that are now exposed on land in Spain and Morocco respectively. Red stars indicate the IODP drilling sites. Red triangles indicate the location of onshore drilling with ICDP.

Keynote - André Bahr

Paleoceanography and Gateways

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The opening and constriction of oceanic gateways shaped global climate throughout Earth's history. In this presentation, two examples for feedbacks between gateway dynamics and climate change during the Neogene will be discussed. The first case study will focus on the water mass exchange between Atlantic and Mediterranean via the Strait of Gibraltar since the Miocene. Although small in volume flux (0.7 Sverdrup, Sv = 10^6 m^3 s^{-1}), the warm and saline Mediterranean Outflow Water (MOW) has an enormous impact on the salinity and heat budget of the North Atlantic Ocean. Recent studies demonstrate that its production is essentially paced by the East African Monsoon, due to the MOW's formation in the eastern Mediterranean Basin. Based on proxy data and numerical modelling, a tight connection of enhanced MOW production and anomalous heat transport into the high latitudes of the North Atlantic could be established for crucial turning points in Earth's climate history, such as the Plio-Pleistocene transition, the mid-Pleistocene and the Heinrich Stadials of the last glacial. The ensuing anomalous warming at high latitudes had severe consequences on the ice-sheet stability and growth in the North Atlantic realm: it might have contributed to reduced ice-sheet growth during the Plio-Pleistocene transition and aided ice-sheet destabilization during Heinrich Stadial 1, while it may have led to enhanced ice-sheet growth during the Mid Pleistocene via enhanced moisture transport.

In a second case study, the climatic impact of the flooding and submergence of the Bering Strait during the Plio-Pleistocene and its influence on the Atlantic Meridional Overturning Circulation will be examined. Alike the Strait of Gibraltar, the volume flux through the Bering Strait appears rather minute (0.8 Sv). However, a closure of the Bering Strait blocks an important exit of freshwater derived from the large rivers entering the Arctic Ocean which is now forced to discharge into the North Atlantic. Freshening of the North Atlantic efficiently reduces deep water formation and thus suppresses the Atlantic Meridional Overturning Circulation with global consequences. Although the importance of the Bering Strait for the Arctic Ocean and North Atlantic freshwater budget is undisputed, constraining the exact timing of its shoaling is highly complex due to interaction of isostatic uplift and eustatic sea level rise.

Both case studies demonstrate that even seemingly small-scale changes in the configuration of ocean seaways have the capacity to fundamentally alter the global climate system if they occur at neuralgic points, e.g. close to areas of deep-water formation. Incorporating the flow through Bering Strait as well as Gibraltar into Earth System models is hence vital to reliably simulate the interaction of tectonics, sea level, oceanography and climate.

Seismic stratigraphy of the Guinea plateau: a 150-Myr history of structural deformation, sediment routing and magmatism

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The Guinea Plateau, offshore Guinea, and Guinea Bissau contains a record of the stratigraphic and structural evolution of two major rift events – the Jurassic opening of the Central Atlantic and the Cretaceous opening of the Equatorial Atlantic. Despite the geologic significance of the Guinea Plateau, little research has been carried out on its depositional and tectonostratigraphic evolution. In this study, 2D regional seismic reflection constrained by biostratigraphic data from wells on the Guinea margin were interpreted to define a high-resolution seismic stratigraphic framework, to reconstruct depositional environments through time, and to constrain the timing of Mesozoic to Cenozoic structural and magmatic events.

Seismic stratigraphic analysis reveals four tectonostratigraphic units: (i) a Jurassic syn-rift megasequence, (ii) a late Jurassic to Early Cretaceous Central Atlantic post-rift sequence, (iii) a late Early Cretaceous syn-transform sequence, and (iv) an Upper Cretaceous to Cenozoic post transform sequence. These megasequences record late Jurassic thermal subsidence (after the Central Atlantic rifting) and subsequent platform carbonate deposition. This was, followed by the progradation of four distinct episodes of early Cretaceous (Barremian – Albian) delta systems, that shut down the carbonate factory, marking the first major input of clastic sediment to the margin. The Upper Cretaceous is characterized by four distinct transgressive – regressive cycles, separated by major flooding surfaces and in some cases type-1 sequence boundaries. The Cenozoic sequence is characterized by distal clastic deposition and thick Mass Transport Deposits (MTDs) on the Guinea Terrace. These sequences are linked to dynamic topography and large-scale changes in sediment routing to the Guinea Plateau.

The top of the Albian sequence is marked by a pronounced erosional unconformity, truncating an intensely faulted Early Cretaceous sequence. This represents the break-up unconformity of the Equatorial Atlantic. Deformation continued into the Early Cenomanian along the Guinea Marginal Ridge (GMR), along the southern margin of the Guinea Plateau. This is interpreted to be the result of transpressional uplift in a post-rift, syn-transform structural regime, prior to full separation of the African and South American plates. Structural interpretation shows evidence of Cenozoic intra-plate hotspot volcanism occurring as shallowly buried extrusions along the northern fringe of the Guinea Fracture Zone (GFZ). They formed because of decompression melting and extensional activity restricted to the Guinea Fracture Zone. Onlapping relationship suggests a late Palaeocene to Eocene age, and the emplacement mechanism is related to short-lived, multiple ‘plumelets’ upwelling from a superplume, taking advantage of weak zones. A potential local impact on the thermal regime and maturation of source rocks is postulated.

These results document the stratigraphic archive of multi-phase tectonics, geodynamics, volcanism and sediment routing, all of which have an important effect on the evolution of the Guinea Plateau and surrounding regions.

Impact of the Pyrenean Gateway on deep-water circulation in the NE Atlantic during the Middle and Late Cretaceous

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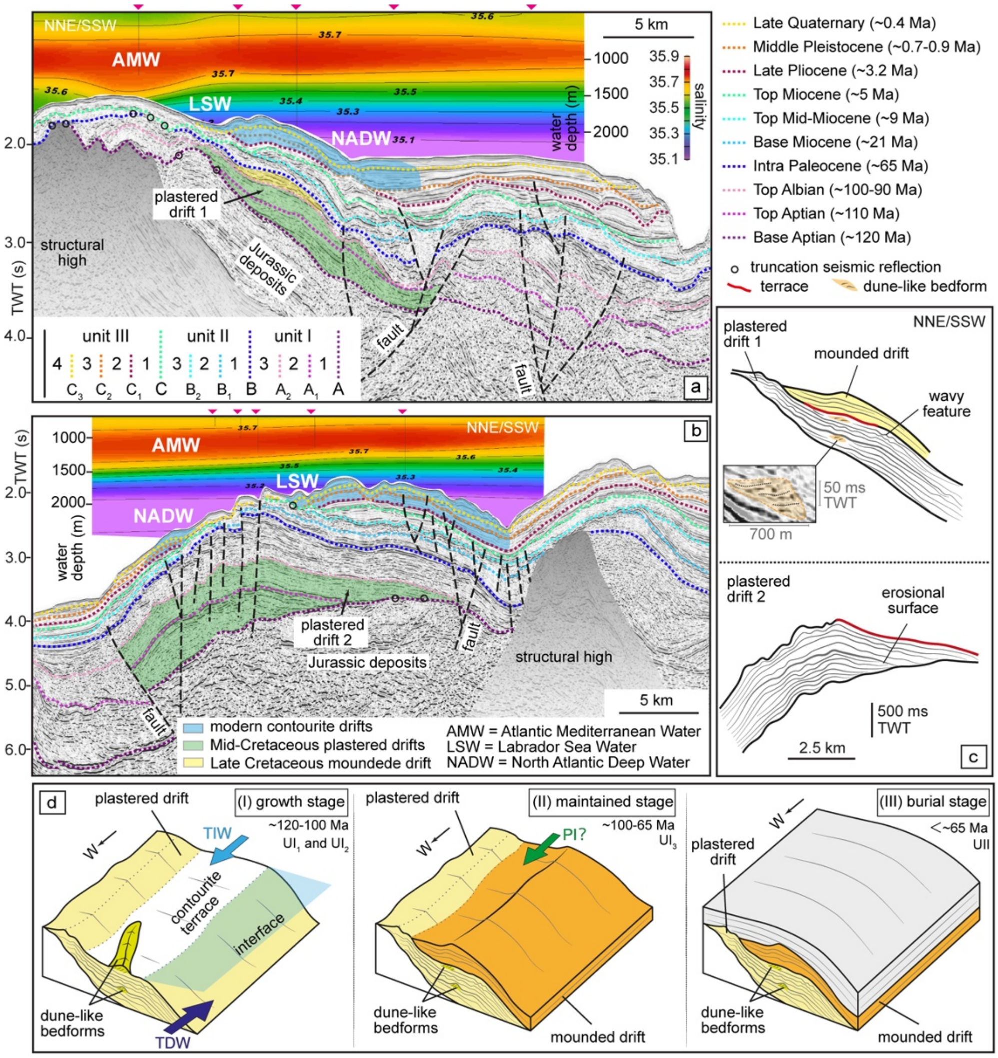
The Cretaceous circulation and deep-water mass exchange were profoundly controlled by marine gateways (Hay, 2009). The connection/gateway between the Tethys and the Atlantic (proto-Strait of Gibraltar) served as a primary route for deep-water circulation in the NE Atlantic (Dunlap et al., 2013; Soares et al., 2014). Beyond that, another marine gateway, geographically referred to as the Pyrenean Gateway, was formed between Europe and Iberia during the Cretaceous. Studies on the oceanographic consequence of this gateway, however, remain sparse. This work uses seismic reflection data, tied to the biostratigraphically-calibrated well MC-B3 (Shell España), to describe bottom current (contourite) features formed in the southern proto-Bay of Biscay.

Three major seismic units (UI, UII, and UIII), 10 subunits, and associated seismic discontinuities are identified. A buried contourite depositional system including two plastered drifts (in UI_1 and UI_2), associated erosional surfaces, and a mounded drift (in UI_3) are recognized (Fig. 1). The E-W orientated plastered drifts are numerically designated as plastered drifts (PD) 1 and 2 and have a Mid-Cretaceous age. Wavy features and dune-like bedforms are shown along the flat top surface (terrace) of PD-1. The E-W orientated mounded drift was generated atop PD-1 and has a Late Cretaceous age. The major changes in the sedimentary stacking pattern and the outlined chronology in the study area suggest three stages for the construction of the Cretaceous contourite depositional system: I) growth stage (~120 to ~100-90 Ma), II) maintained stage (~100-90 and 65 Ma), and III) burial stage (<~65 Ma) (Fig.1). The Tethyan Intermediate and Deep water and their interface would be responsible for generation of plastered drifts during the Middle Cretaceous (growth stage). The mounded drift was most likely shaped by the Polar Water during the Late Cretaceous (maintained stage). The burial stage indicates a transition from the Cretaceous to the Cenozoic oceanic circulation in the NE Atlantic.

Shifts in the dominated water masses in the southern proto-Bay of Biscay suggest that profound changes in ocean circulation occurred at ~100-90 and ~83-65 Ma, linked to three major events: 1) the closure of the Pyrenean Gateway; 2) the opening of the Equatorial Atlantic Gateway; and 3) the tectonic setting of the Rio Grande Rise-Walvis Ridge. There might be numerous undiscovered contourite outcrops in continental sections of western Europe, given that the Tethyan Intermediate and Polar water flowed across these regions during the Late Cretaceous. These contourite outcrops could provide fundamental implications for the sedimentary facies and sequence model of contourites, as well as for the paleoceanography and paleoclimate of Cretaceous Earth.



PI = Polar waters; TIW = Tethyan Intermediate Water; TDW = Tethyan Deep Water

Figure 1 (a, b) Seismic and oceanographic joint profiles showing the main seismic units, subunits, and discontinuities. Contourite drifts are indicated; (c) External geometry and internal seismic configuration of the Cretaceous contourite drifts; and (d) Evolutionary stages of the Cretaceous contourite depositional system. The colours in the oceanographic profiles represent the salinity of the present-day water masses.

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Late Cretaceous palaeotemperature records from the Australian southern margin: a link between temperature and the opening of the Australo-Antarctic Gulf?

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The Late Cretaceous (100–66 Ma) was a period of major climatic and tectonic change, with global cooling following the collapse of the mid-Cretaceous hothouse (~94 Ma) and the final break-up of Gondwana. Rifting between Australia and Antarctica opened a new seaway—the Australo-Antarctic Gulf—the history of which is poorly constrained and yet it plays a key role in the Southern Ocean circulation. Here we present new sea-surface temperature (SST) records, based on the organic geochemical proxy TEX_{86}, from IODP Expedition 369 to the southern Australian margin. Data from the Gulf and the adjacent Mentelle Basin allow a comparison of temperature evolution at both sites, and to investigate the link between temperature and changing oceanography and/or tectonism.

Our data show temperatures in the Australo-Antarctic Gulf (AAG) ranged from 24–35°C (Figure 1), whereas those in the Mentelle Basin were 28–37 °C. Immediately following the peak warmth of the mid-Cretaceous, temperatures in the AAG were much cooler than sites at comparable latitudes, and the stark difference in temperatures between the sites demonstrates the relative isolation of the Gulf. The AAG experienced punctuated warming during the Turonian–Coniacian (~93–88 Ma), and the stabilisation of temperatures thereafter, whereas the Mentelle Basin and other high-latitude sites cooled steadily from the Turonian onwards. These changes may be attributed to oceanographic and/or tectonic drivers.

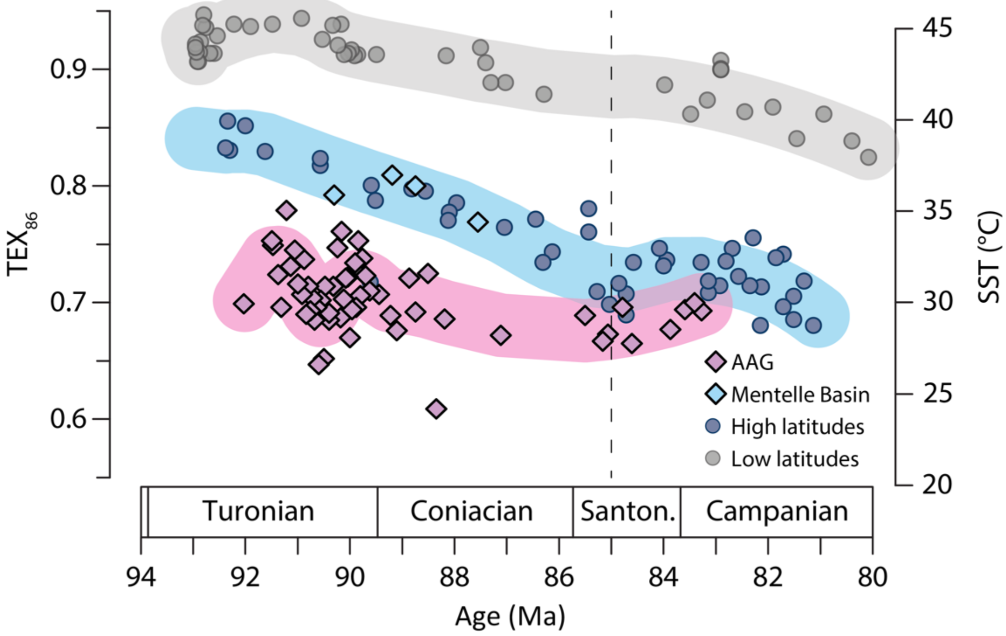

Figure 1. New Australo-Antarctic Gulf (AAG; pink squares) and Mentelle Basin (blue squares) TEX_{86}-SSTs compared with existing southern high-latitude (blue dots) and low-latitude (grey dots) TEX_{86}-SSTs. SSTs are calculated using the BAYSPAR calibration.

(1) The warmer temperatures of the late Turonian correspond to a major carbon-cycle perturbation and period of higher sea level and may reflect episodic incursion of warmer Tethyan waters during periods of highstand. Alternatively (or additionally), the current consensus is that seafloor spreading commenced between Australia and Antarctica at ~84 Ma. The convergence of global and AAG SSTs could be explained by either of these interpretations, as each scenario would lead to a considerable depression between the two plates that would be filled by seawater.

(2) The restricted AAG would likely have inhibited the development of strong surface currents that could advect water into the Gulf. The Turonian palaeogeography of the Indian Ocean (Figure 2) allowed for easterly currents at 50˚S under the Southern Hemisphere westerly belt, but only a poorly developed subpolar gyre circulation between 55–60˚S. However, as the Cretaceous progressed, the northward migration of the Indian Plate could have provided the space for a subpolar gyre to develop, bringing cooler waters to the Mentelle Basin and across the gateway into the AAG.

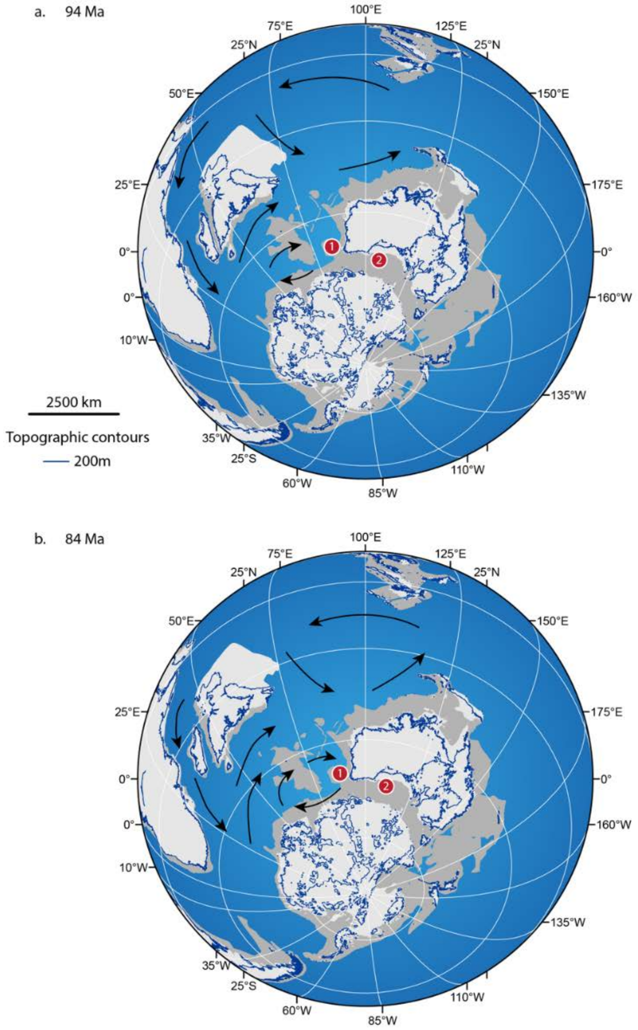

Figure 1. Plate tectonic reconstruction showing the inferred upper ocean circulation based on TEX_{86}-SST records during the Turonian (94 Ma) and Campanian (84 Ma). The Mentelle Basin (1) and Australo-Antarctic Gulf (2) are indicated by red spots.

Bottom current sedimentation as an indicator for the onset and evolution of the Indo-Australian Oceanic Gateway

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Submarine gateways play a critical role in the exchange of water-masses, the modification of ocean circulation and the control of deep-water processes amongst others (Sijp et al., 2005). Although the tectonic, geochemical and stratigraphic evolution from rift to passive margin in northwest Australia has been broadly studied (e.g., Tindale et al., 1998; Longley et al., 2002; Reeve et al., 2016), there is a very poor understanding of when the oceanic gateway formed between Indian and Australia during the major Mesozoic tectonic events that led to the their separation and sedimentary implications. The Northern Carnarvon Basin (offshore northwest Australia) is a particularly interesting sedimentary basin which hosts a submerged marginal Plateau (the Exmouth Plateau) at 800-3000 m water depth (Fig. 1A). This basin has not only proven useful for the identification of morphosedimentary features, but also for decoding their relationship with depositional processes, plate tectonic motions and gateways development. Regional extension began during Paleozoic, followed by Triassic to Jurassic rifting events, which involved the successive rotation and dispersion of continental blocks until the final separation of Greater India from Australia in the Lower Cretaceous (Longley et al., 2002; Hall, 2012; Reeve et al., 2016).

This study used an extensive dataset of 2D multi-channel reflection seismic combined with exploration wells and Ocean Drilling Program (ODP) site data (Fig. 1B) to document the sedimentary evolution of the basin and constrain palaeoceanographic models for its regional surroundings. Seven seismic units (SU1-SU7; Fig. 2) bounded by regional discontinuities (D0- D6) are defined from the outer shelf to the middle slope. Variations in the stratigraphic stacking pattern of these units and morphosedimentary features within them suggest five major evolutionary stages (Fig. 3): 1) the first stage (latest Tithonian-late Valanginian) sees large plastered and mounded drifts develop, they mark the beginning of a new oceanic circulation pattern where bottom currents interact with local gravitational processes resulting from the Greater India – Australia breakup; 2) the second stage (Hauterivian-late Turonian) shows extensive erosional (moats) and depositional contourite features (sheeted, plastered and mounded drifts) form under the influence of enhanced bottom currents associated with the opening Indo-Australia Seaway, gravitational processes are reduced during this time; 3) during the third stage (Coniacian-late Eocene) the Indo-Australia Seaway widens and deepens, northward flowing water-masses strengthen promoting increased growth of contourite features. This occurs coevally with an increase of gravitational processes which cause incisions, the development of submarine channel systems and the formation of a mixed (turbidite-contourite) system in the Kangaroo Trough between the Campanian and late Eocene. Here, asymmetric levees suggest an interplay between gravitational and bottom current processes; 4) during sage four (Oligocene-late Miocene) prograding clinoforms document a substantial change in stacking pattern and depositional style across the continental shelf and upper slope, bottom currents predominate around the Exmouth Plateau however; and 5) the final stage (Pliocene-Quaternary) is coeval with the collision of northern Australia with the Banda Arc, plastered drifts reappear along the upper slope which form under the influence of enhanced modern day bottom currents.

Our findings suggest that water-masses and bottom currents have continuously influenced the northwest Shelf of Australia (Northern Carnarvon Basin). The onset of ocean circulation occurred between the latest Jurassic and earliest Cretaceous with water-masses entering the region via a narrow gateway that developed during the initial separation of India from Australia. Thus, the flow of water-masses into the region resulted in an ocean circulation which has been recorded within the sedimentary stacking pattern of the continental margin. The Exmouth Plateau represents a key structural feature that enhanced local bottom current velocities and influenced the long lasting development of contourite features. This study provides further evidence showing how the opening and closure of oceanic gateways is a long-term driver of paleocean circulation, one that can gratly affect deep-marine sedimentation along continental margins.

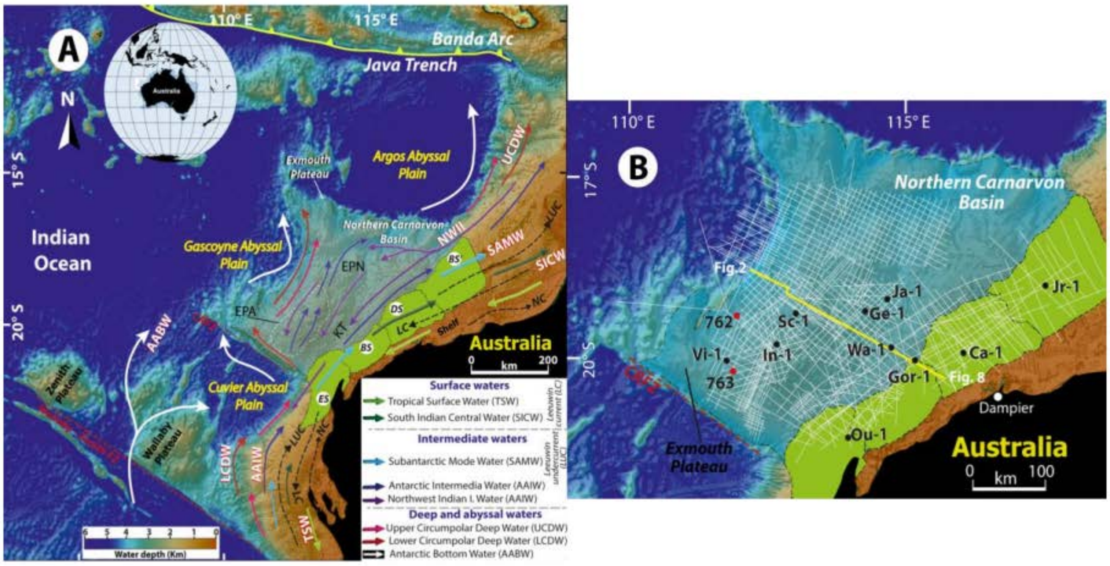

Figure 1. (A) Shows the location of the Northern Carnarvon Basin (offshore Northwest Australia) as well as the main physiographic elements and the distribution of the Exmouth (ES), Barrow (BS), Dampier (DS) and Beagle (BS) sub-basins. The Exmouth Plateau divides into three main areas referred to as the Kangaroo Trough (KT), Exmouth Plateau Arch (EPA) and Exmouth Plateau North (EPN). The Regional distribution of modern-day water masses is also shown. Bathymetry data courtesy of Geoscience Australia. (B) Shows the distribution of 2D seismic surveys (white) and well data used in this study, as well as the referencedseismicprofile in Fig. 2(yellow line), ODP (red dots) andexploration wells (black dots). Well abbreviations: Vink-1 (Vi-1), Investigator-1 (In-1), Outtrim-1 (Ou-1), Glencoe-1 (Ge-1), Gorgon-1 (Go-1), Warrior-1 (Wa-1), Scarborough-1 (Sc-1), Jansz-1 (Ja-1), Jarman-1 (Jr-1), Campbell-1 (Ca-1). Elevation and bathymetric data courtesy of Geoscience Australia. Outlines of the sub-basins were compiled from Bilal et al. (2018).

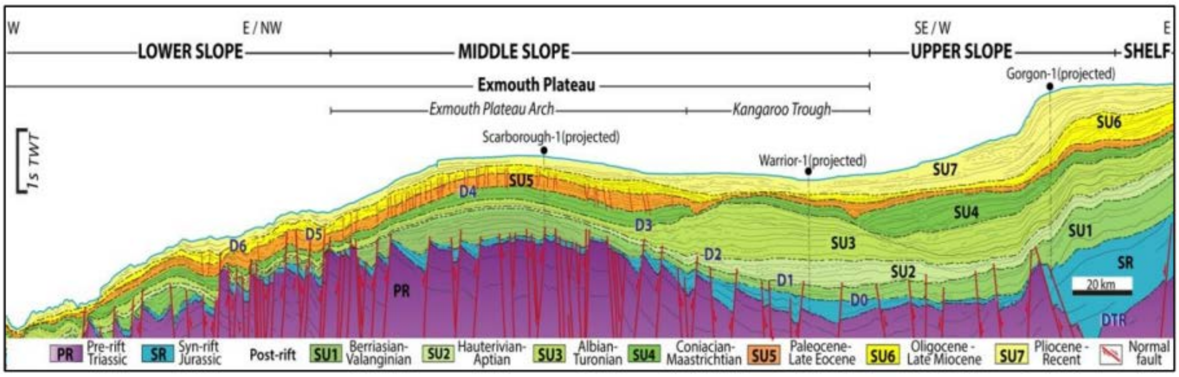

Figure 2. Interpreted regional seismic profile of the Northern Carnarvon Basin. The profile shows the seismic units (SU1-SU7) and discontinuities (D0-D6), the external mound geometries referred to within the text are exhibited in the units. Note the large mounded deposit formed during SU3 over the Kangaroo Trough region. Seismic line location given in Fig. 1B.

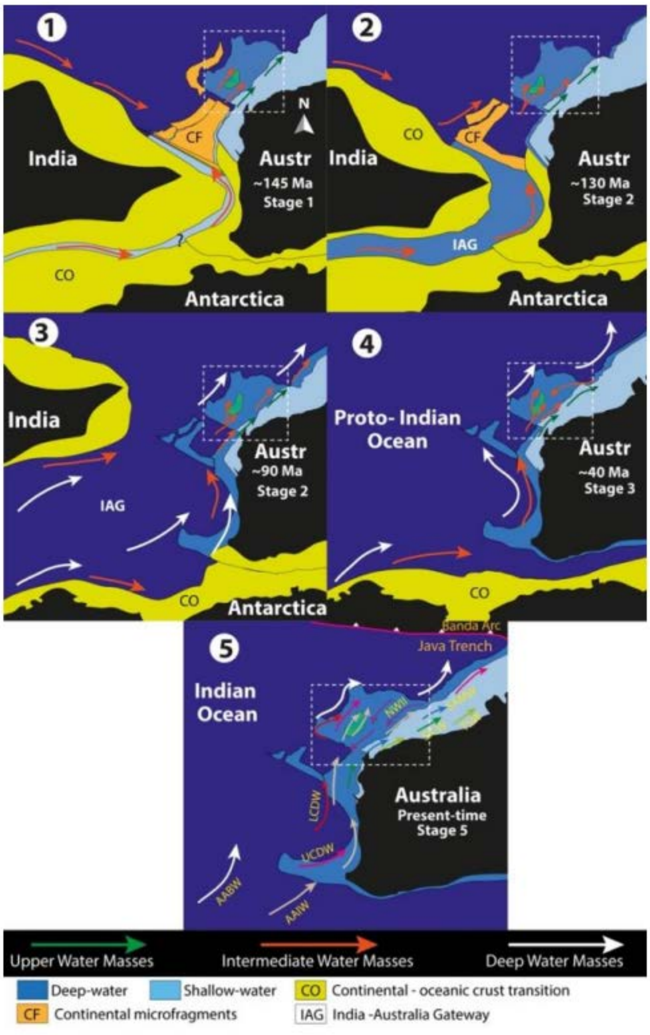

Figure 19. Palaeoceanographic evolution of the Northern Carnarvon Basin based on results and interpretations from this study for: 1) 145 Ma, 2) 130 Ma, 3) 90 Ma, 4) 40 Ma, 5)

Present. Palaeogeographic reconstructions based on Gibbons et al. (2012; 2013), Hall (2012), and palaeoenvironment reconstructions based on Longley et al. (2002).

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Contourite depositional systems within the Orange Basin, South Africa

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The Orange Basin along the western margin of South Africa is home to different water masses that reside at various depths. Of these, the cold Benguela Current (BCC) is a major surface current, while the Antarctic Bottom water current (AABW), the Antarctic intermediate water (AAIW), and the North Atlantic deep water (NADW) are bottom currents. The BCC and AAIW flow northwards, while the AABW and NADW flow southwards (Figure 1a). These currents have been mapped by researchers from the Alfred Wegner Institute (AWI) and occur in the area covering nearly 200000km^2 within the basin. They have sculpted the margin in some shape or form since the Aptian to the present-day. During the Aptian we observe associated features such as sediment waves, mounds, channels while the Cenozoic has numerous drifts, moats, and furrows. Contourites are sediments formed by along slope bottom water currents (BWCs) (Rebesco & Stow, 2001) and can be grouped together and referred to as contourite depositional systems (CDS) (Thiéblemont, 2019).

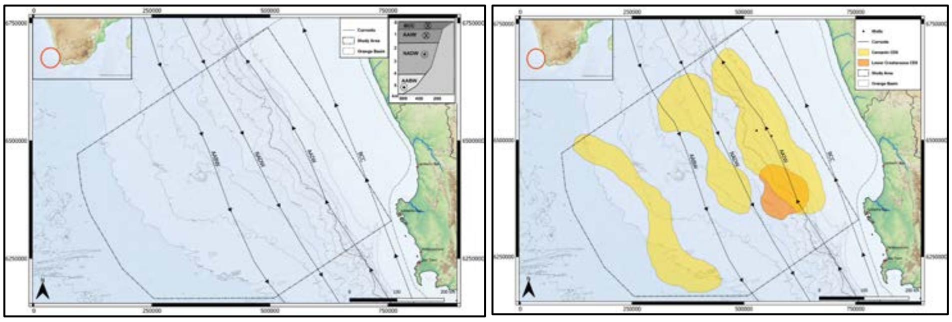

Figure 1 a) The BCC, NADW, AABW and AAIW along the margin b) Four contourite depositional systems (CDS) mapped in the basin extending from the shelf break to abyssal plain

2D multichannel seismic evidence of a CDS situated 300km from the shelf on the abyssal plain, suggest the influence of the currents are farther reaching (Figure 1b). Two primary contourite depositional systems (CDS); A Cenozoic CDS dispersed across and below the seafloor, and a smaller lower Cretaceous CDS have been identified on 2D multichannel seismic (Figure 1b). They extend from just off the present-day continental shelf in water depths of 195m onto the abyssal plain in water depths of 4750m. The Cenozoic CDS comprises of three systems and cumulatively is roughly 86500km^2 in size, while the lower Cretaceous located in the south covers an area of about 8000km^2. The length of the Cenozoic CDS varies between 330km to 445km, and it is 23km to 140km wide. In contrast, the lower Cretaceous CDS is about 120km in length, and up to 110km wide (Figure 1b). The three CDS's closest to the coast, have their formation likely attributed to the interaction of the AAIW, AABW and NADW bottom currents, while the third is primarily formed due to the action of the AABW (Figure 1b&2a). The interaction between especially the AAIW and NADW bottom currents is expressed by larger drifts and moats of different shapes and sizes on seismic, postulated to be the result of eddies which in turn may be caused by this intermixing of obverse flowing currents (Figure 2b). The CDS's encompass various depositional features represented by drifts, mounds, sediment waves, erosional in the form of moats, channels, and furrows and mixed features like terraces throughout the sedimentary column in the basin (Figure 2). Contouritic elements become subtler distally owing to the weakening influence of the currents coupled with gentler slopes. Proximally we observe massive contouritic depositional features in the form of large plastered and elongated mounded drifts primarily caused by the AAIW, reaching sizes up to 8100km^2 while smaller plastered drifts distally are 1300km^2 in size. Elongated mounded drifts are up to ~11600km^2 in size (Figure 2a). Large erosional elements are demonstrated by moats, contouritic channels and furrows. The NADW current exhibits smaller features relative to the AAIW current where low relief contouritic lenses are observed.

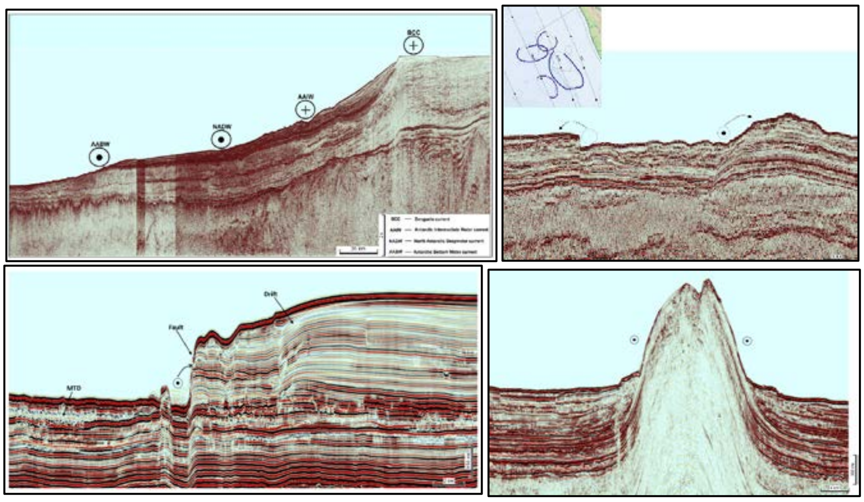

Figure 2 a) Approximate positions of the BCC, AAIW, NADW, AABW along a seismic transect b) Postulated eddies and resulting drift and erosional features c) Fault controlled drift and associated MTDs d) Large seamount acting as a possible hindrance to current flow in the north of the basin

Fault controlled contourites are observed with associated sediment failure shown by mass transport deposits (MTDs) at the seafloor (Figure 2b&c). An 800m high seamount seen on seismic may act as a hindrance to the NADW current flow and lead to eddy generation (Figure 2d). Distally contouritic elements shift from contouritic lens deposits to sediment waves, furrows, and ripples. The AABW displays contouritic features such a relatively small abyssal "patch" drifts with lens like geometry (Figure 2a). The BCC is restricted primarily to the present-day shelf, the AAIW to the shelf break and upper slope, the NADW to the upper slope and the AABW to the lower slope in the north and rise in the south (Figure 3).

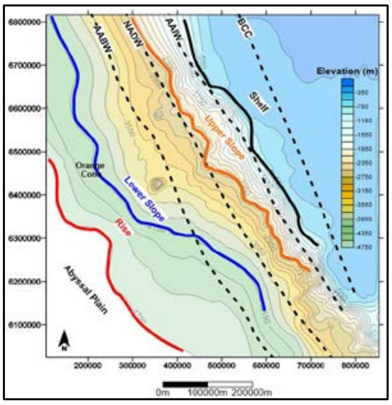

Figure 3 BCC, AAIW, NADW, AABW and their location along the present-day environments of the continental margin

Summary

Four currents located at different depths are present in the area covering almost 200000km^2 within the basin. They have affected the shape of the margin since the Aptian to the present-day resulting in a variety of features. Currents reach beyond their existing position based on seismic data. Two contourite depositional systems (CDS) are identified in the basin.

Formation of certain contouritic features is attributed to the interaction of the bottom currents. Intermixing of opposing flowing currents possibly create eddies which form bigger features. We observe a connection between bottom currents and mass transport deposits at the seafloor.

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The impact of Atlantic paleogateways on the growth of ancient mixed depositional systems: Paleoceanographic, sedimentary and economic implications

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Oceanic gateways have influenced the global oceanic circulation and climate since ancient times. During the Mesozoic, the breakup of Pangea, and most importantly of Laurasia (which began with the separation of North America from Eurasia at ~215-175 Ma in the Late Triassic to Early Jurassic and which lasted until ~56 Ma in the Paleocene) and Gondwana (characterized by the separation of Africa from South America between ~180-125 Ma in the Early Jurassic to Early Cretaceous) created a series of oceanic ridges and gateways across the Atlantic Ocean (e.g., the Walvis Ridge-Rio Grande Rise, the Falkland-Agulhas Seaway and the Equatorial Atlantic Gateway). These ancient gateways allowed water mass exchange between the South and North Atlantic Oceans, forming an intermediate and deep-water circulation regime. Local current acceleration across the structural ridges and oceanic gateways, along with the progressive deepening of the South and North Atlantic Oceans, contributed to an active global circulation and the formation of mixed (turbidite-contourite) depositional systems during the Early to Late Cretaceous.

This study summarizes the effects of the Atlantic paleogateways on the formation of ancient mixed depositional systems, as well as their contribution to paleoceanography, sediment supply and economic potential. Key examples are presented in the South and North Atlantic, such as the Argentine and Uruguayan Cretaceous mixed systems established in the Southern Hemisphere and the Nova Scotian Cretaceous to Eocene mixed systems developed in the Northern Hemisphere. 3D seismic data, 2D broadband seismic surveys and chronostratigraphic well data was employed to investigate the sedimentary stacking patterns of these mixed depositional systems and decode their relation to the opening and closing of major Atlantic paleogateways.

Detailed seismostratigraphic interpretations of key examples revealed an onset stage which began around ~89 Ma in the South Atlantic and around ~125-120 Ma in the North Atlantic, suggesting that an initial paleocirculation was established in the Early to Late Cretaceous across both basins. This paleocirculation was initially isolated within each basin, as there is no evidence of water mass exchange across the Atlantic paleogateways. In the Late Cretaceous, all mixed systems developed thick sedimentary stacking patterns and unilateral migration, suggesting that a bottom current intensification began to occur during that period. In the North Atlantic, bottom current intensifications appear to have occurred at ~101, ~94, ~78 and ~50 Ma, whereas they occurred around ~81 and ~66 Ma in the South Atlantic. Furthermore, all the mixed systems that were developed across the South Atlantic appear to have suffered a bottom current inversion at ~81 Ma, whereas the mixed systems built across the North Atlantic appear to have been influenced by changing bottom currents around ~78 Ma. These bottom current changes suggest that incursion and exchange of Atlantic-derived waters began to occur during the Late Cretaceous, which is most likely tied to the opening of the equatorial Atlantic gateways between ~100 and ~80 Ma. Therefore, water mass overflow across the Atlantic paleogateways significantly affected the previously established circulation patterns.

All mixed systems transition to dominant contourite depositional systems during the Paleogene (after >50 Ma in the Northern Hemisphere and >66 Ma in the Southern Hemisphere), suggesting that the gradual opening of the South and North Atlantic Oceans, along with the submersion of the Atlantic paleogateways, led to the establishment of a global oceanic paleocirculation. Other mixed systems have given rise to similar interpretations, suggesting that ancient paleogateways exerted major controls on the global oceanic paleocirculation. Furthermore, the restriction or invigoration of the Cretaceous to Paleogene paleocirculation most likely had a significant effect on the North and South Atlantic petroleum plays as the along-slope bottom currents were responsible for carrying and redistributing sediments along the continental slope and rise.

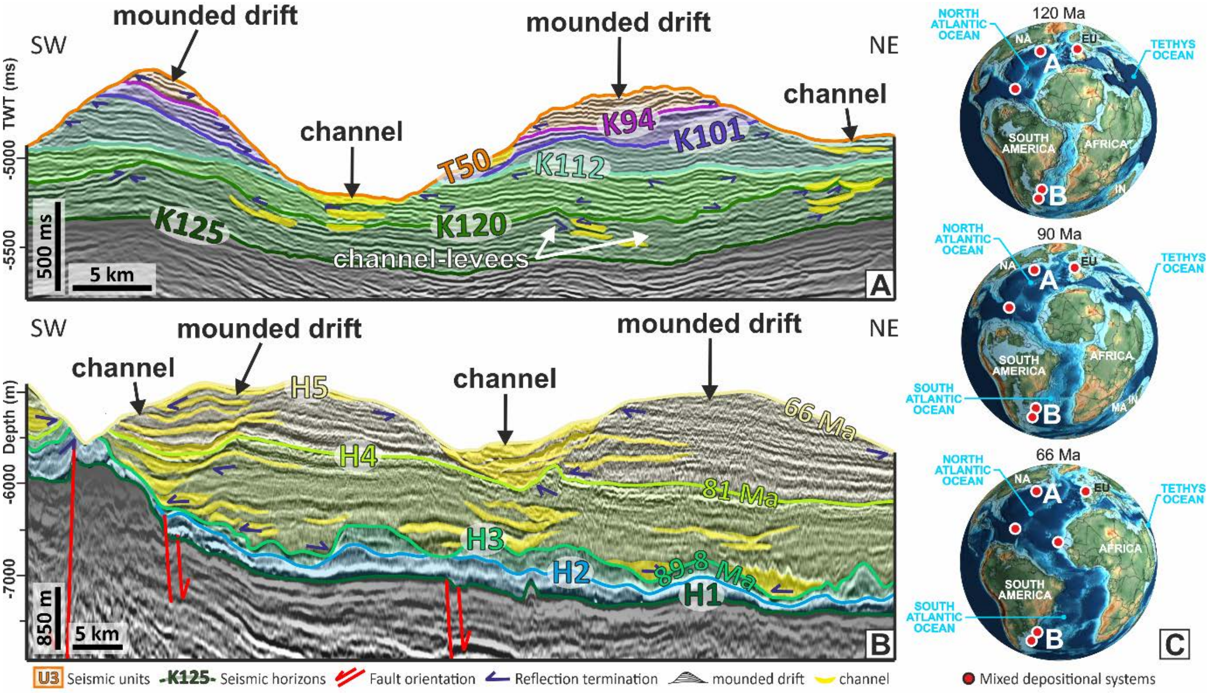

Figure 1. (A, B) Key examples of ancient mixed (turbidite-contourite) depositional systems developed offshore Nova Scotia and Argentina. (C) Paleogeographic reconstructions of the Early to Late Cretaceous and Paleocene after Scotese and Wright (2018).

This work offered, for the first time, a closer look at the impact of oceanic paleogateways on the Cretaceous global paleoceanographic circulation, as well as their contribution to the formation of mixed depositional systems along the North and South Atlantic margins. As shown, oceanic paleogateways can induce local- and global-scale variations in the intermediate- and deep-water circulation regimes, which play a fundamental role in regulating climate, maintaining marine ecosystems and transporting sediment. Their impact has only been studied for a few years, but significant results have already been yielded which highlight the significance of paleoceanography and its associated processes. Future research should focus on recognizing other ancient mixed depositional systems built across the North and South Atlantic Oceans, to resolve the picture of how the Atlantic paleogateways affected the Cretaceous paleocirculation and paleoclimate at different temporal and spatial scales.

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Eocene to middle Miocene contourite deposits in Cyprus: a record of Indian Gateway evolution

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Bottom current deposits (contourites) form in association with modern day or ancient oceanic gateways. A paucity of examples in the ancient record and lack of consensus on diagnostic criteria for differentiating them from other deepwater deposits limit our understanding of how they may record past global oceanic circulation, tectonic events and gateway evolution. This work describes an exceptional example of Eocene to middle Miocene deep-marine deposits nowadays located both onshore and offshore deepwater environments around the island of Cyprus. Multidisciplinary approaches were used to discriminate contourite facies associations, propose a sedimentary model, and interpret the relations with regional tectonics and the opening of the nearby Indian Gateway. Contourite deposits appear in late Eocene to middle Miocene intervals interstratified with pelagic/hemipelagic sediments, turbidites and mass-transports deposits (MTDs). These deposits developed along a slope basin located on the upper plate of an active margin evolving from a wide basin developed during a period tectonic quiescent into a series of shallowing-upward, segmented sub-basins affected by compressional stress. This work proposes a sedimentary model in which two contourite depositional systems developed: first in the Eocene (dominated by finer-grained contourites), and then during the latest Oligocene to middle Miocene (dominated by coarser-grained contourites). Both systems were buried by extensive marl deposits and record the respective influence of deep (circulating NW) and intermediate (circulating SE) water masses. The long-term evolution of the contourites reflects tectonic events that enhanced subduction processes south of Cyprus as well as exchange between the Neotethys Ocean and the Indian and Atlantic Oceans —until the final closure of the Indian Gateway by the end of the middle Miocene, when a new circulation pattern was established with the formation of the Mediterranean Sea.

The contourites deposits represent bi-gradational sequences that normally form in association with contouritic drifts, sometimes having the asymmetric top-cut sequence characteristics of plastered drifts and contourite terraces. The coarser (sandy) contourites, formed from the latest Oligocene to middle Miocene, consist of three packages associated with compressive and flexural phases. They pertain to I) Chattian (late Oligocene); II) Aquitanian/Burdigalian (early Miocene) and III) Langhian (middle Miocene). Evidence of enhanced bottom current episodes occurs toward the top of these packages before they are buried by later dominant marl deposits. The sandy contourites thus formed during the compressive phases, whereas the predominately finer-grained units formed during later flexural phases. The intermittent turbidites and MTDs (developed during compressional phases in combination with pelagic/hemipelagic sediments) represent the sediment supply for the contourite deposits after their winnowing and / or reworking. This research found that the diagnostic criteria for discriminating ancient bottom current deposits from other deepwater deposits are related primarily to variations in sedimentary processes, current velocity, sedimentation rates and paleoenvironmental conditions. This highlights the importance of primary sedimentary structures, microfacies and ichnological features in making determinations at the sedimentary facies scale.

This work demonstrates the role of plate tectonics and oceanic gateways in driving the paleo oceanic circulation that, in turn, controls sedimentary processes and shapes the morphology of oceanic basins and continental margins. It also allows for comparison with other present-day and ancient continental margin deposits. Future similar high-resolution approaches and analyses of other study areas could help resolve the sedimentary architectures of deepwater systems in terms of episodic tectonic processes —involving compressive-flexural stress variations— in different geological settings. They control the Earth's surface environment (sea-level, climate and oceanic circulation) over time by influencing sediment supply, packages of strata and types of contourite deposits.

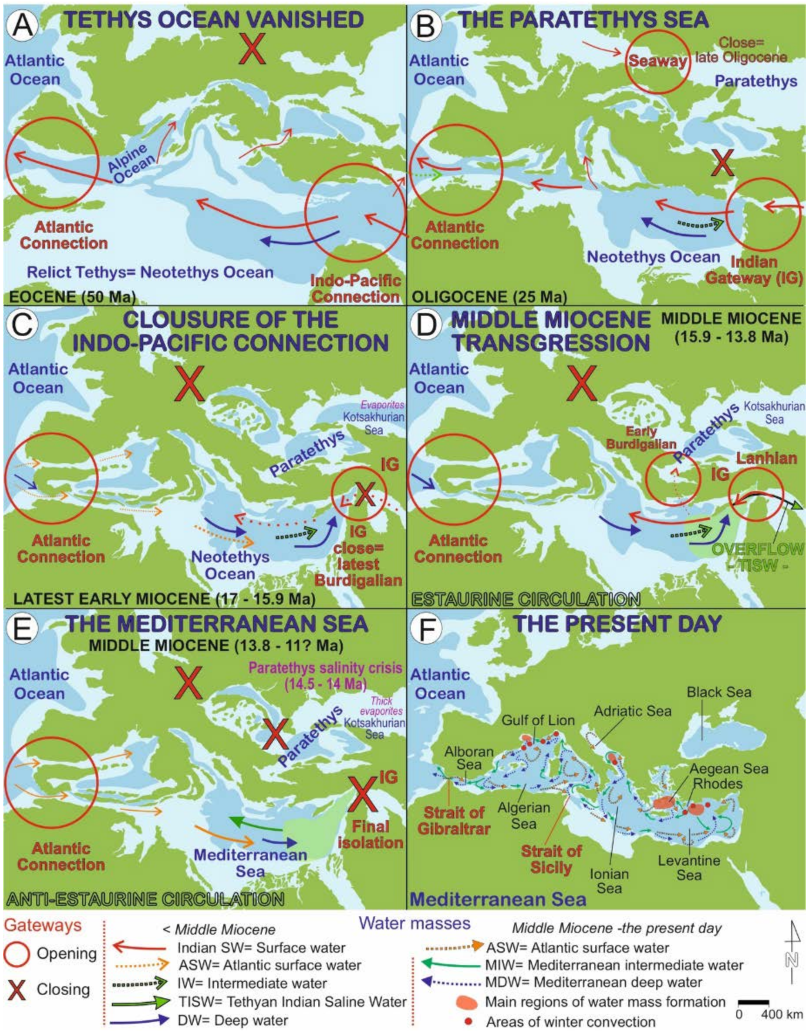

Figure 1. Paleo-reconstructions of Eocene (A), Oligocene (B), latest early Miocene (C), middle Miocene (D and E) and present day (F) for the Neotethys Ocean and Mediterranean Sea, including regional distribution of surface, intermediate and deepwater masses, and the key opening and closure of gateways, especially for the Indian and Atlantic Gateways. Eocene finer-grained contourites developed in A, but the coarser (sandy) contourites packages

were developed in B (package I, Chatian, late Oligocene); C (package II, Aquitanian/Burdigalian, early Miocene); and D (Package III, Langhian, middle Miocene).

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Ichnological record on Gateways and other high-energy deepwater environments

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Oceanic gateways play a key role in controlling global ocean circulation and climate systems. These regions can determinate significant variations in global ocean circulation and climate over relatively short periods of time inducing important changes in paleoenvironmental (i.e., depositional and ecological) conditions and therefore, impacting in the living biota. Contourites and bottom current-controlled deposits have been recognized in several settings including modern day and ancient oceanic gateways, especially shallow ones. However, comparatively scarce examples refer to deep-ancient gateways, even closing and opening of main gateways determined drastic changes in the deep-water circulation. To a better understanding of ancient deep-ancient gateways and the incidence of bottom-currents, several contourites outcrops have been studied focusing on the ichnological analysis. Trace fossils, as reflecting the behaviour of trace makers, reveal their response to depositional and ecological factors (e.g., salinity, oxygen, nutrients, hydrodynamic energy, rate of sedimentation, etc.); thus ichnological analysis helps to characterize bottom currents deposits associated to high-energy deepwater environments of gateways.

During the late Miocene, the Atlantic Ocean and the Mediterranean Sea were connected through the Rifian Corridor (Morocco). This gateway is one of the few examples of deep ancient seaways with a semi-continuous sedimentary record. Deposits comprise turbidites, intercalated between deep-sea mudstone (i.e., hemipelagites and drift deposits), and channelized sandstone contourite facies. Turbidite deposits are typified by vertical trace fossils (i.e., *Ophiomorpha*), conforming the *Ophiomorpha rudis* ichnosubfacies. Contouritic sandstone exhibits high density and low diversity trace-fossil assemblage, with predominant *Macaronichnus* and *Scolicia*, resembling a proximal expression of the *Cruziana* ichnofacies. Hydrodynamic energy reveals as the major factor controlling trace maker communities in the studied seaway. Highly energetic conditions contribute to ichnodiversity impoverishment in ichnofacies. The incidence of bottom currents on the trace maker community depends not only of flow strength, but also on the interplay between food supply and seafloor heterogeneity.

The opening of the nearby Indian Gateways influenced Eocene to middle Miocene deep-marine deposition in Cyprus. Contourite deposits appear interstratified with pelagic/hemipelagic sediments, turbidites and mass-transports deposits (MTDs). Two contourite depositional systems developed: first in the Eocene (dominated by finer-grained contourites), and then during the latest Oligocene to middle Miocene (dominated by coarser-grained contourites). Ichnological analysis of the carbonate contourite drift shows the ichnofacies replacement from the *Zoophycos* ichnofacies to the distal-archetypal-proximal *Cruziana* ichnofacies, revealing more energetic and proximal environments. Thus, the bottom current hydrodynamics and sedimentation rate are determinant in the distribution of the macrobenthic trace maker community.

To support the incidence of bottom currents on macrobenthic trace maker community in ancient high-energy deepwater environments, the analysis of modern counterparts can be a tool. Thus, modern biogenic traces (lebensspuren) have been studied in abyssal stations (4000m depth) affected by benthic storms events. Ichnological analysis, including identification of lebensspuren morphotypes and relative abundance, before, during and after high-energy episodes, revealed bioturbational changes with the general impoverishment in both diversity and abundance of lebensspuren assemblages during benthic storms. In this context, resuspension of unconsolidated seafloor sediments led to the reorganization of organic matter resources, determining changes in the benthic community. Relationship between bottom currents/nutrients/macrobenthic communities is revealed not only in the abundance and composition of lebensspuren, but also in changes in movement patterns of deep-sea bioturbational fauna. Thus, echinoid movement patterns, composed of straight and meandering paths, reveal significant changes related to spatial distribution of nutritional resources on the seafloor.

This research demonstrates the impact of bottom currents/nutrient availability on macrobenthic trace maker community inhabiting deepsea environments, and the usefulness of ichnological analysis to understand involved processes, with comparison between modern and ancient examples as the most valuable approach. Bottom currents deposits associated to deep-ancient gateways show impoverished trace fossil assemblages and local abundance of particular ichnotaxa, and modern deepsea environments affected by benthic bottom currents reveal changes in lebenssupen diversity and abundance, and in trace morphology.

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Session Three: Data integration &multidisciplinary analysis

Mapping Ocean Gateways from 3D Seismic Data: Modern Seafloor and Ancient Analogs

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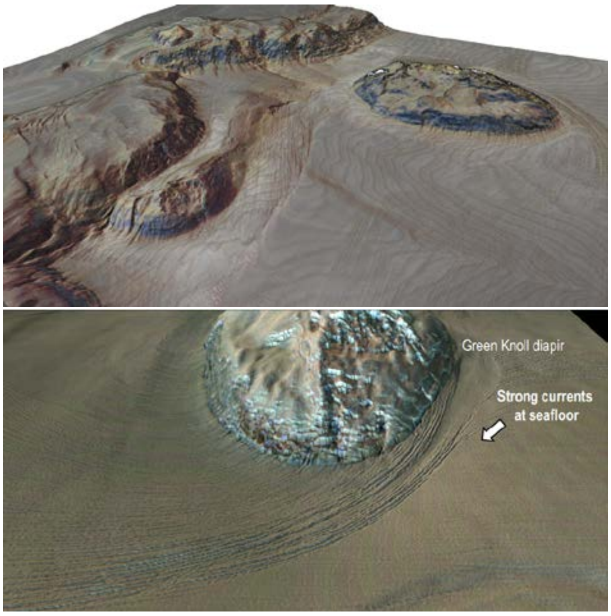
The mapping of marine depositional environments in the context of their geologic and stratigraphic history can be achieved on local to regional scale from every larger 3D seismic data. When interpreting seismic data using the color processing method (Laake 2015), lithologic and depositional maps can be extracted that in turn provide clues for ocean currents at the time of deposition. This approach provides high vertical resolution down to 5 m and can be applied to both, the modern seafloor and representations of ancient seafloors anywhere inside the seismic data cube. Since modern and ancient seafloors are represented in a similar way, both may serve as examples for geologic analogs.

For the demonstration of the depositional mapping capabilities from seismic data two case histories have been selected:

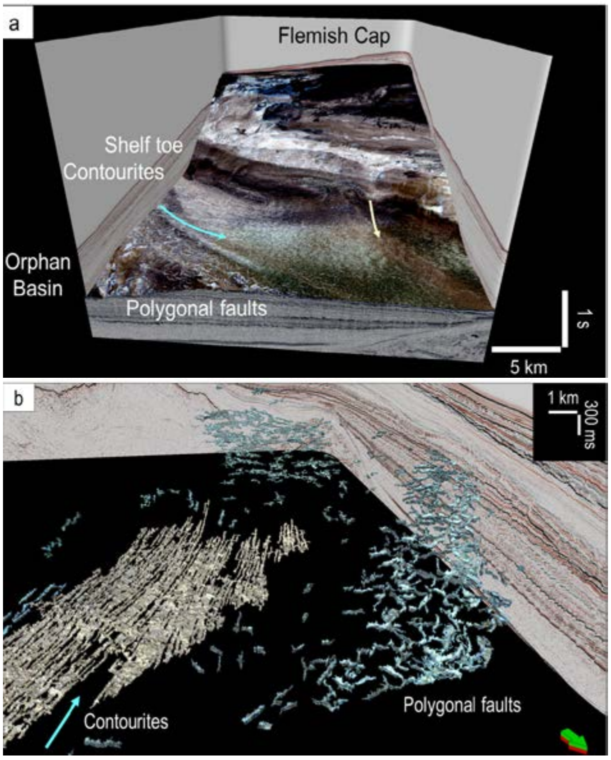
1. Modern seafloor at Green Knoll just south of the Sigsbee Salt Canopy in the USA Gulf of Mexico (Laake et al. 2014) : rapid seafloor currents parallel to the salt escarpment flowing around the Green Knoll salt diapir leaving up to 50 m deep furrows in the seafloor. These can be interpreted as the trace of a horse-shoe vortex rolling up on the flanks of the salt diapir. The color processing method enhances the topographic representation of the furrows through the lithologic differences between the furrows and the country rock.

2. Ancient seafloor at the toe of the slope from Flemish Cap into the Orphan Basin northeast of Newfoundland, Atlantic Canada (Laake et al. 20170. In the Lower Tertiary, deposition of sands and shales occurred down the slope of Flemish Cap into the Orphan Basin. Sand prevails close to the slope, which is replaced increasingly by shale towards the basin. Perpendicular to this slope deposition, an ocean current – the predecessor of the modern Gulf Stream – created drift deposits which can be detected in the seismic volume from their different acoustic impedance. The color processing method allows even to isolate the sand contourites as geobodies, that could be indicative of reservoirs.

The geologic interpretation of color processed 3D seismic data provides texture on modern and ancient horizons the color of which is representative of lithology and can in turn be interpreted for depositional environments. Furrows indicate rapid currents parallel to the seafloor, the shape of sand geobodies embedded in a shale-dominated host rock indicates drift processes overlaying gravity-driven deposition down the continental slope. 3D seismic data provide the added benefit of including the overlying and underlying strata into the interpretation whereas ever increasing size of these seismic volumes provides regional to basin context.



Modern seafloor at southern escarpment of Sigsbee Salt Canopee (left) and furrows from horseshoe vortex around salt diapir (Laake & Wolfe 2015)



Tertiary contourite depositional environment at Flemish Pass (left) and contourites extracted as geobodies (Laake et al. 2017)

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Using seismic data to image water masses – sedimentation interactions at the Demerara plateau offshore Surinam and French Guyana.

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The Demerara Plateau is a submarine Transform Marginal Plateau (TMP) located along the South American continental margin offshore Surinam and French Guyana at the boundary between the Central and Equatorial Atlantic oceans. Together with its conjugate, the Guinea Plateau, it formed during rifting and represented probably a last landbridge between the Equatorial Atlantic and Central Atlantic ocean basins. These last landbridges accumulate sedimentary deposits and are today archives of sedimentary and oceanographic processes. Also, they directly influence the ocean currents by inhibiting ocean-wide circulation before separation and by modifying coast parallel currents, as they constitute bathymetric highs beyond the classic continental shelf

From their formation during transform or highly oblique rifting, the Demerara and Guinea plateaus inherited a steep slope morphology, making them prone to frequent mass wasting processes. The Demerara plateau can be divided into three main physiographic domains: the upper plateau with a mean slope of 1°, the intermediate plateau with a slope of 4° and the lower plateau, showing a slope of around ~1°. The steep morphology caused abundant landslides in the past and a prominent slope failure headscarp separates the upper from the intermediate domain where slope values are higher, 4° in average. These mass slides are typically found on TMPs and they can be the origin of geological hazards for submarine cables or seafloor installations and also potentially at the coast as they might trigger tsunamis.

One open question is the origin, tectonic or oceanographic, of these submarine landslides. Earthquake hazard along the passive continental margin of French Guyana and Suriname is considered very low. Thus, an alternate origin of the slides might be the interaction between sedimentary and oceanographic processes, for example by slope over-steepening from rapid sedimentation at the top of the plateau or erosion from rapid currents at its foot. A third proposition is that internal waves in the ocean influence the sediment stability, locally leading to mass wasting.

Images of the sedimentary structures and bathymetric maps of the Demerara plateau were acquired during the IGUANES, GUYAPLAC and DRADEM cruises. Along the intermediate slope seafloor, NW-SE oriented sediment depositional bedforms may also record the activity strong ocean currents. Elongated NW-SE depressions including “comet tails” shaped by strong currents are present more distally on the intermediate plateau where mass transport deposits outcrop. They seem to record the NW to SE flow of strong currents. Erosion of the lower slope by currents might lead to over-steepening of the slope and destabilisation of the sedimentary units. Seismic data from these cruises allowed to identify at least 12 stacked large scale mass wasting deposits, recording a past of large-scale slope failure. Numerous fluid escape features are identifyable in the bathymetric data and in this environnement the presence of fluids and the steep slopes of the plateau might also be at the origin or contribute to the mass wasting processes.

Detailed measurements of the water masses were acquired during the CITHER cruises. The sedimentation processes of the intermediate and deep part of the Demerara plateau are controlled by deep-sea currents, principally influenced by three different water masses : the Antarctic Intermediate Water (AAIW) flowing from the SE to the NW between 550 and 1200 m depth ; the North Atlantic Deep Water (NADW) flowing from NW to the SE between 1200 and 4200 m depth and the cold and dense Antarctic Bottom Water flowing from SE to NW at water depths greater than 4200 m.

During the recent MARGATS cruise a network of 8 deep sounding seismic profiles was acquired spanning the Plateau with the underlying geological stratigraphy as main objective. However, as high amplitude seismic sources were used during the data acquisition, these profiles image the different water masses as well. The processing sequence for the seismic data in the water column included muting the direct arrival on the seismic streamer, filtering, velocity analysis and stacking of the traces. The oceanographic and geologic parts of the profiles were then combined using different gains on the two data sets (Figure 1).

The transition from AAIW to NADW water masses is marked by a high amplitude reflection package. Additional oceanographic data, bathymetric and seismic profiles allow to compare the water mass boundaries to morpho-sedimentological expressions on the seafloor. A clear correlation exists between the slope failure headscarp and the base of the boundary between the AAIW and NADW located at ~1500 m water depth. The analysis of bathymetric and oceanographic parameters suggests that critical bottom slopes might have been reached allowing internal wave generation between the upper and intermediate plateau. This work from the Demerara Plateau illustrates how seismic data from the water column help to decipher the interaction between sedimentary and oceanographic processes that shape the sea floor.

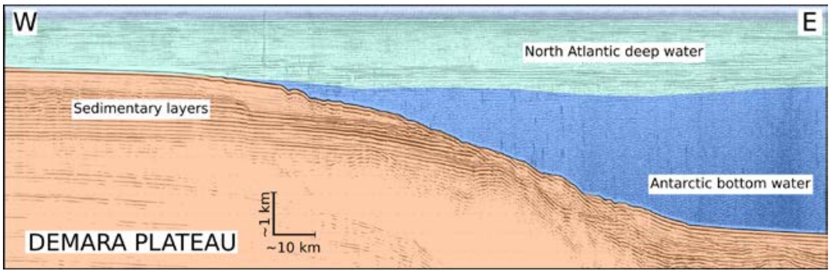

Figure 1: Combined seismic data from the water column and the sedimentary layers of the Demerara Plateau.

Session Four: Gateways in Polar regions

Fingerprints of geological-scale change in the Antarctic Circumpolar Current: Insights from the present day

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The Antarctic Circumpolar Current (ACC) – a system of ocean currents that flows eastward along a ~25,000 km-long path encircling Antarctica – plays a crucial role in Earth's climate by connecting the three major ocean basins, allowing the establishment of a global overturning circulation, and isolating Antarctica from warm subtropical waters. At present, views of the geological-scale evolution of this climatic role commonly highlight the dependence of the ACC's intensity on (i) the width of the circumpolar channel, and (ii) the strength of the winds and air-sea buoyancy fluxes acting on the Southern Ocean. However, recent observations and advances in dynamical understanding portray a potentially different picture, in which the large-scale ACC flow is relatively resilient to changes in topography and surface forcing at the expense of a range of oceanic turbulent phenomena. The evidence for this picture will be outlined here, as will be the lessons drawn for the interpretation of geological proxies.

Modelling the role of seabed topography to the life and fate of dense overflows in Antarctica

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Dense water overflows (DWOs), also known as dense shelf-water cascading, are an important oceanographic process that occurs in certain polar and temperate margins when surface waters over the continental shelf become denser than surrounding water and eventually sink, overflowing the shelf edge and cascading downslope. This process generates a near-bottom gravity-driven turbulent flow that involves the massive transfer of energy and matter from shallow to deep waters. The formation of dense water in Antarctica is restricted to a few areas (Fig. 1) and its spreading over Antarctic slopes is crucial to produce Antarctic Bottom Water (AABW), a key actor of the global thermohaline circulation. During the last decades we have observed a progressive weakening of dense shelf water formation and export in Antarctica (Amblas and Dowdeswell, 2018; Kusahara et al., 2011; Menezes et al., 2017; Snow et al., 2018), which reflects the variability of these complex ice-ocean systems and their sensitivity to climate change. Within this fragile context it is necessary to understand the physical processes involved in the concentration and propagation of DWOs, and to quantify their capacity to erode, transport and deposit sediment.

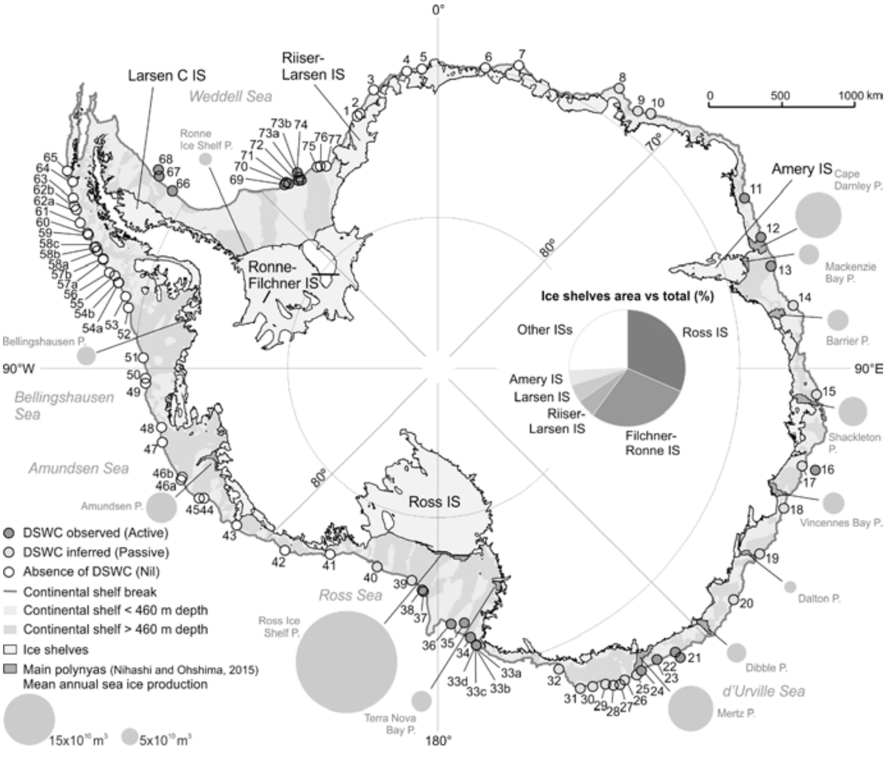

Fig. 1. Location of water column observations showing the presence (dark grey dots) or absence (white dots) of dense overflows in Antarctica. The coastline and ice shelf areas are derived from the SCAR Antarctic Digital Database. The 460 m contour and the continental shelf break are based on IBCSO v. 1.0 (Arndt et al., 2013). The major coastal polynyas and values of mean annual sea ice production are taken from Nihashi and Ohshima (2015). The size of the grey circles is proportional to the polynyas sea ice production. The 88 hydrographic observations compiled are all located at or near the shelf break. Confirmed DSW cascade observations are 27 in total and are located in East Antarctica, Ross Sea, East Antarctic Peninsula and Ronne-Filchner. IS: ice shelf; P: polynya. Modified from Amblas and Dowdeswell (2018).

We tackle this objective by adapting a process-based depth-integrated numerical model, which was initially developed at IFREMER to simulate turbidity currents. The model, named Nixes-Tc (Jacinto and Burel, 2003), allows to numerically reproduce bottom dense flows and sediment suspensions within different ambient water masses and along complex topographies, and it provides a quantification of the associated transport, erosion and deposition of sediments. To define the model initial and boundary conditions we use the database gathered in the review by Amblas and Dowdeswell (2018) (Fig. 1). For the topography we create a set of generic terrain models that capture the main morphologic elements observed in glacial margins, where the main volumes of DWOs have been reported. This is a wide, deep and landward-sloping continental shelf with crossing troughs, and continental slopes with convex (i.e. canyon) and concave (i.e. trough-mouth fan) shapes. This set up allows to study the first-order controls of DWOs concentration and propagation in high-latitude margins and provides a better understanding of the physical dynamics and their capacity to erode, transport and deposit sediment (Fig. 2). This can result into improved geomorphic and stratigraphic predictions in these settings characterised by mixed sediment gravity flows - bottom current systems.

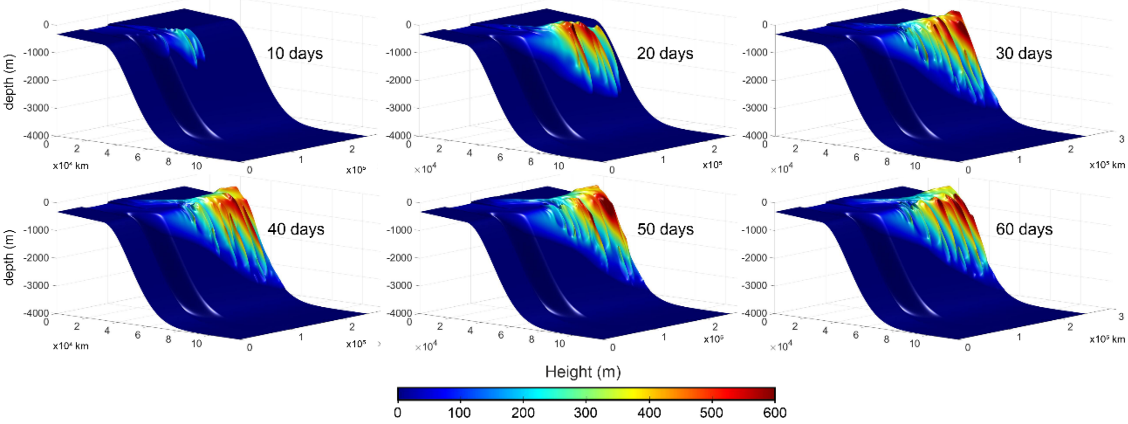

Fig. 2. Nixes-Tc modelling results showing the evolution, during 60 days, of DWOs over a synthetic terrain model that recreates a typical glacial margin, with a cross-shelf trough and a submarine canyon. Initial flow conditions have been adopted from Ross Sea (Antarctica) observational mooring data.

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The role of Southern Ocean gateway opening in the evolution of Southern Ocean surface oceanography: latitudinal gradients, subpolar gyres and the Antarctic Circumpolar Current

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The oceanographic and climatic consequences of the widening of Southern Ocean gateways remain enigmatic. Although atmospheric CO_2 decline is generally seen as the main driver of trends in Cenozoic climate, ocean and Antarctic ice sheet conditions, questions remain what secondary role the tectonic opening of the Tasmanian Gateway and Drake Passage have played in these trends. We provide insights into the oceanographic consequences of late Cenozoic (35–5 Ma) gateway changes by utilizing organic walled dinoflagellate cysts (dinocysts) and organic biomarkers (TEX_{86}) from marine sedimentary drill cores across the Southern Ocean. While dinocyst assemblages provide a powerful tool to reconstruct surface ocean conditions (sea ice, nutrients, temperature, salinity), biomarker proxies provide quantitative reconstructions of sea surface temperature (SST). We compare our reconstructed latitudinal SST gradients and frontal system migrations to model experiments and tectonic reconstructions to deconvolve the effects of climate, ice volume and tectonic changes on the Southern Ocean oceanographic evolution. In the Tasmanian Gateway region our results show a persistent SST gradient between southern Australia (ODP Site 1168) and Antarctic-proximal Wilkes Land (IODP Site U1356) of ~ 6–10°C prior to 26 Ma, followed by a steady increase in temperature gradient from ~26 Ma onwards, due to a progressive decrease in Antarctic-proximal SSTs. This is inconsistent with the decrease in Late Oligocene global benthic foraminiferal $\delta^{18}O$ record indicating ice mass loss/deep sea warming. The timing of cooling does coincide with deepening of Drake Passage and fits well with results of ocean model experiments, suggesting enhanced thermal isolation and Antarctic-proximal cooling at gateway opening. In the South Atlantic, east of the Drake Passage our records show a stepwise breakdown of the large South Atlantic subpolar gyre, towards the modern-like oceanographic regime with strong frontal systems and latitudinal gradients in temperature and nutrients. We demonstrate that while climate and ice volume changes determine the strength of meridional SST gradients and position of ocean fronts on orbital time scales, gateway configurations play a large role in long-term trends.

IODP Expedition 382: a tale from scientific drilling in the Drake Passage

Lara F. Pérez

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The Drake Passage, together with the Tasman Strait, is key to understand the circulation patterns of the Southern Ocean and their implications for ice sheet growth and decay. In the Drake Passage, the Scotia Sea is formed by continental banks generated during the breakup of the former bridge between South-America and the Antarctic Peninsula. They bound small isolated oceanic basins which sedimentary record documents the regional tectonic, oceanographic and climatic evolution since the Eocene. International Ocean Discovery Program (IODP) Expedition 382 'Iceberg Alley' recovered for the first time the upper sedimentary record of two of these basins. The sedimentary analyses, accurate age constraints, and high-resolution physical properties obtained from the drilled sites, correlated to the regional reflection seismic profiles, have resulted on several scientific publications that highlight the global implications of the Drake Passage evolution. According to our results, the outflow of Antarctic Bottom Water to northern latitudes controlled the Antarctic Circumpolar Current flow from late Miocene. Subsequent variability of the Antarctic ice sheets has influenced the oceanic circulation pattern linked to major global climatic changes during early Pliocene, Mid-Pleistocene and the Marine Isotope Stage 11. Climate variability is linked to the glacial/interglacial cyclicity, and has influenced the latitudinal migration of the polar fronts.

Does tectonics or climate control Atlantic Meridional Overturning Circulation through the Greenland-Scotland Ridge oceanic gateway?

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Fluctuations in the Atlantic Meridional Overturning Circulation (AMOC) over timeframes from decades to millions of years, including a slow-down over the last few decades unprecedented in over a millennium, exert a fundamentally important influence on climate. At present, the AMOC carries a quarter of northward global atmosphere-ocean heat transport and is the single largest carbon sink in the northern hemisphere. Cold, deep oceanic flow across the Greenland-Scotland Ridge (GSR) directly contributes about one third of the AMOC, and indirectly influences the remainder. Throughout Neogene time, fluctuations in the cross-sectional area of the GSR oceanic gateway may have influenced AMOC strength and northern hemisphere climate. This presentation will discuss the extent to which the AMOC is influenced by the climate system itself and by tectonic development of the GSR oceanic gateway.

In the Tectonic Lock Gate (TLG) theory, vertical motions of the GSR gateway influence AMOC strength and northern hemisphere climate on time periods of 100 kyr to 10 Myr throughout Neogene time, and possibly throughout the Cenozoic. The TLG theory states that when water depth at the GSR decreases, the reduction in cross-sectional area of the gateway leads to weakening of the AMOC, and thus to cooling of the Nordic Seas and surrounding continents. The changes in relative sea-level at the GSR are on a scale of several hundred metres, and are caused by fluctuations in dynamic support (i.e. mantle convective support) associated with thermal pulsing of the Icelandic Mantle Plume.

The TLG theory is supported by multiple lines of evidence including core-derived sedimentary records of environmental change, oceanic crustal records of magma productivity, and climate system modelling. Since late Miocene time, proxy records for dynamic support are inversely correlated with the %NCW (Northern Component Water) proxy for AMOC. In particular, shallowing of the GSR lock gate (i.e. increased dynamic support) during the late Pliocene correlates with an inferred weakening of AMOC that could have contributed to intensification of the Northern Hemisphere Glaciation. The strength and pathways of deep seawater currents are recorded by the accumulation rates of contourite drift sediments in the North Atlantic Ocean, including the Eirik, Bjorn, Gardar, Hatton Drifts. Changing drift accumulation rates imply an increase in AMOC strength during the mid-Pliocene period when the GSR lock gate was lower (i.e. increased water depth). Furthermore, increasing the cross-sectional area of the GSR by a factor of about 2.5 in a fully coupled ocean-atmosphere model (HadCM3) without changing other model parameters results in increases in both AMOC and Arctic sea surface temperature (>5°C).

In contrast, our new comparison of the chemical composition of deep sea water either side of the GSR does not support the TLG theory. We compared the carbon and neodymium isotopic signatures of deep water in ODP Hole 642B (Norwegian Sea, north of the GSR) and DSDP Hole 552A (Rockall Plateau, south of the GSR) across the Pliocene epoch. The data suggest that the Norwegian Sea and Rockall Plateau deep waters were *more* chemically isolated during the middle Pliocene relative to present. At this time, the TLG theory predicts that deep waters either side of the GSR should be *less* chemically isolated because dynamic support of the GSR was relatively low (i.e. relatively deep water) and the %NCW proxy for AMOC was relatively high.

Fluctuations in the AMOC that are more rapid than any tectonic driver also correlate with climatic changes. Examples include changes in the location of North Atlantic oceanic fronts during stadial-interstadial (millenial-scale) cycles, and a slow-down of AMOC over the last few decades unprecedented in over a millennium. In the latter example, high-latitude warming correlates with *weakening* of AMOC, whereas high-latitude warming is inferred to correlate with *strengthening* of AMOC in the TLG theory.

These apparent contradictions underscore our need to improve understanding of the complex links between ocean circulation, climate and gateway tectonics on different timescales. To progress understanding requires a clearer picture of which components of AMOC alter, why and how. For example, the "GSR gateway" actually comprises two sub-gateways: Denmark Strait and the Iceland-Faroe Ridge. Our comparison of the chemical compositions of the Rockall Trough and Norwegian Sea deep waters probably implies that flow through the Iceland-Faroe Ridge sub-gateway did not conform to the TLG theory during the Pliocene, but no coeval indicators of flow through the Denmark Strait sub-gateway are yet available. We suggest that an international effort to obtain sediment core-based records that can distinguish the relative contributions of deep water flow through Denmark Strait and the Iceland-Faroes Ridge to the AMOC would be fruitful.

Underexplored continental shelf gateways: timing, mechanisms and role of SW Barents Sea Gateway, Norwegian Arctic

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Ocean gateways connecting ocean basins are crucial for water and heat circulation, which influence global temperature, climate evolution and sediment distribution. While deep-water gateways have been a major research focus by the community, very little attention has been drawn to shallower gateways located on the continental shelves, where such circulation also takes place. In this study, we investigate the evolution of a shallow gateway in SW Barents Sea that presently connects NE Atlantic and Arctic oceans. This gateway contributes to about half of the Atlantic–Arctic water exchange, whereas the other half is occurring through the deeper Fram Strait Gateway. When and how this SW Barents Sea Gateway formed are debated and still poorly understood. Outcomes from this study will thus be relevant for regional and global models of ocean circulation. Moreover, this study will contribute to climate evolution models over longer timescale in a climate sensitive region where an Arctic amplification of warming is presently seen.

Unlike opening of Fram Strait and other typical deep-water gateways, which was the results of rifting and seafloor spreading between two continents, the reconstructions of SW Barents Sea Gateway also involve vertical tectonic components such as sediment loading, isostasy and thermal subsidence. This gateway has been affected by a complex tectonic break up in the early Cenozoic (c. 55 Ma) that involved rifting and transtensional component, and a major ice-sheet development in the late Cenozoic (c. 2.7 Ma) that involved ice loading and glacial erosion, and their isostatic compensations. These events have influenced the spatial variation and temporal evolution of the formation of this gateway. We apply a 3D sequential backstripping technique to produce paleobathymetrical maps for the early Eocene (c. 55 Ma), mid Eocene (c. 40 Ma), Oligocene (c. 33 Ma), Miocene (c. 23 Ma) and Plio-Pleistocene (c. 2.7 Ma). The main input for the model was a set of depth-converted maps interpreted from 2D and 3D seismic data that were tied to well data. Key crustal structures and parameters (e.g., Effective Elastic Thickness, Beta factor maps) were tested to generate realistic reconstructions.

Our reconstructions show that shallow marine to subaerial exposure has largely prevailed in the SW Barents Sea area from the Eocene (c. 55 Ma) to the onset of main glaciations during the Quaternary (c. 2.7 Ma). Subaerial topography was likely enough to block Atlantic Water from entering the BSG in the earliest Eocene (c. 55 Ma). However, this configuration may have allowed the water to enter at a later stage in the Eocene as observed from major basin subsidence and deepening of the structural highs in the mid Eocene paleobathymetry (c. 40 Ma). From the Oligocene (c. 33 Ma) until the onset of the Quaternary (c. 2.7 Ma), basin infilling and shallowing, and regional shelf uplift blocked Atlantic Water from entering the BSG. The slope configuration west of the SW Barents Sea allowed for contourites to be deposited by northward flowing ocean currents from the Miocene onwards.

After c. 2.7 Ma, the SW Barents Sea area deepened and transformed from a subaerial to a submarine platform due to profound glacial erosion and subsidence, and the formation of a trough-mouth fan on the continental slope. This configuration allowed for increased inflow of Atlantic Water through the BSG. Consequently, inflow of Atlantic Water through the Fram Strait was reduced, assuming a constant volume of Atlantic Water entering this area. By constraining a maximum age of c. 2.7 Ma for the BSG, our results imply that the Fram Strait remained the sole gateway for Atlantic Water into the Arctic Ocean since its opening in the Miocene until the Quaternary, whereafter Atlantic Water was also introduced through the BSG. Finally, this study can provide an example of paleobathymetrical reconstruction for other formerly glaciated gateways in Polar areas and other shallow gateways worldwide.

Keynote - Carlota Escutia

Southern Ocean gateways and the development of the Antarctic Circumpolar Current

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The Antarctic Circumpolar Current (ACC) plays an important role on Earth's climate through the global distribution of heat, nutrients, salt, carbon and in the gas exchange between the atmosphere and the ocean. Unabated climate warming is expected to strengthen the southern hemisphere westerlies and cause, among other things, a poleward shift of the ACC transporting eastward Circumpolar Deep Water (CDW). These changes can influence the strength of upwelling, heat and carbon transport, and thus potentially affect the Atlantic Meridional Overturning Circulation and marine carbon storage. In addition, a poleward CDW intrusion into the cavities of marine-based ice sheets can affect their stability through basal melting, thus influencing global sea level. Despite the relevance of the ACC in the Earth Climate System and life on Earth, we have a limited understanding of the evolution of the ACC from its onset until it reached its modern configuration. This knowledge is key if we are to identify past "analogues" to inform the response of the ACC to ongoing and future climate change scenarios projected by the Intergovernmental Panel on Global Change (IPCC) (IPCC AR6, 2021).

It has been long postulated that during the Gondwana break-up, the tectonic removal of the two final land barriers that formed the Drake-Scotia and the Tasman Gateways enabled the development of the ACC in the Southern Ocean (SO). Additionally, the thermal isolation of Antarctica that followed the development of the ACC has long been considered a primary control on the growth of the first continental ice sheet during the Eocene-Oligocene transition (~34 million years-Ma).

Deep-water deposits (i.e., contourite, turbidite and mixed contourite-turbidite systems) help define the Cenozoic history of the opening and deepening of tectonic passages, the onset and evolution of the ACC, and ocean-ice sheet interactions affecting ice sheet stability. Study of these deposits during the last decade points towards a more complex development of the ACC than previously reported. Geological, geophysical and modelling studies show that the opening of the Tasman and Drake Gateways during the middle-late Eocene induced cooler climates and changes in ocean structure and dynamics (e.g., Bijl et al., 2013; Toumoulin et al., 2020; Sauermilch et al., 2021). However, contourite deposits off the eastern Wilkes Land margin do not record the development of a modern-like circumpolar ACC capable of thermally isolating the continent following the opening of the SO Gateways. Instead, the onset of an eastward flowing proto-ACC/CDW is not recorded until ~28 Ma (Fig.1). Furthermore, signatures characteristic of the CDW are recorded on the Atlantic/Indian Ocean side of the Tasman Gateway since the early Oligocene but no homogeneous CDW transport is recorded across the Tasmanian Gateway into the Pacific Ocean between 30 and 20 Ma (Evangelinos et al., 2022) (Fig.2). This implies the presence of a weak and shallow ACC in the Pacific Ocean at least until 20 Ma, which contrasts with today´s inter-basin deep-reaching ACC. These findings are supported by the record from contourite deposits and numerical modelling of the late Oligocene to Miocene that show weaker than present frontal systems allowing the intrusion of warmer CDW waters close to Antarctica (e.g., Salabarnada et al., 2018; Sangiorgi et al., 2018; Hartman et al., 2018; Evangelinos et al., 2020).

The above findings imply that the opening of the Tasman and the Drake Gateways likely played a role, but were not the driving mechanism, in the cooling trend that culminated with the first continent-wide ice sheet growth during the Cenozoic. Furthermore, the development of a modern-like circumpolar ACC capable of thermally isolating the continent after 20 Ma dismisses a direct link between the ACC onset and the growth of the first Antarctic Ice sheet at ~34 Ma. Current results also contradict the previously reported onset of the ACC at ~30 Ma and ~25-23 Ma (Pfhul and McCave, 2005; Lyle et al., 2007; Scher et al., 2015).

Figure 1. Paleoceanographic configuration off the eastern Wilkes Land-Adélie Land margin between 28 and 23.4 Ma based on multichannel seismic reflection data and Integrated Ocean Drilling Program Site U1356.

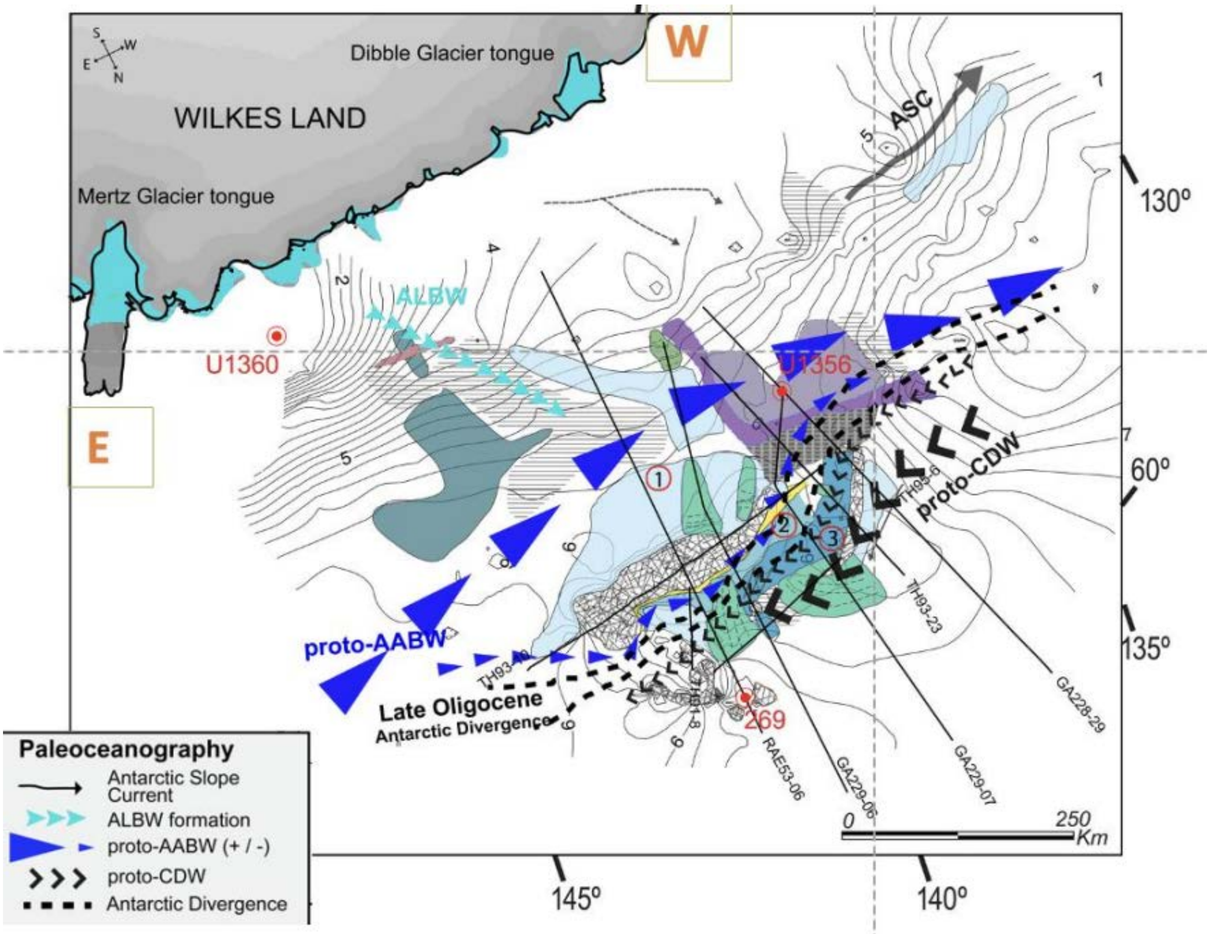
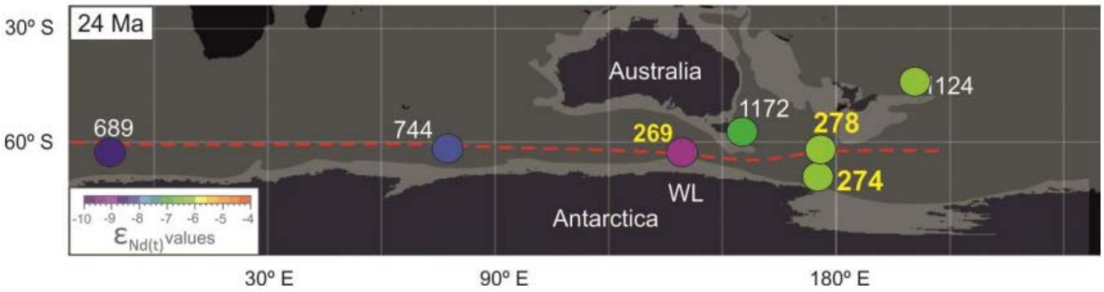


Figure 2. Offset between the Neodymium signature in Ocean Scientific Drilling Sites (Sites 689, 744, 269, 278, and 274) across the Tasmanian Gateway, which contrasts the modern homogenous CDW Nd isotopic composition (from Evangelinos et al., 2022)



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Drake Passage opening: Origins and dispersal of the continental fragments that formed the North and South Scotia Ridges

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Geographic changes associated with Drake Passage opening involved the breakup and separation of South America from Antarctica, opening of the Scotia Sea and the translation of small tectonic blocks to form the North and South Scotia ridges. Today these ridges define the nature of the component flows of the Antarctic Circumpolar Current (ACC), for example, the South Orkney Microcontinent is the main feature of the South Scotia Ridge that dictates the path of the Weddell Sea Deep Water and controls the properties of the Antarctic Bottom Water entering the Atlantic Ocean. How and when these flows first developed, i.e., when open seaways were large enough for circumpolar flows to have an early impact on the global ocean, requires understanding the dispersal history of the continental fragments bounding the Scotia Sea. Although the Neogene tectonic setting of the Scotia Sea is relatively well established, palaeo-locations of many continental fragments prior to dispersal are largely unknown, with almost no geological control on the submerged banks. To gain new insights we applied thermochronometry, geochronology and kinematic modelling to determine the origin of these tectonic blocks and to understand their relationships to the Antarctic and South American plates from the mid-Cretaceous to breakup.

This presentation reviews our work so far. For the North Scotia Ridge detrital age histories of lithologies from the submerged Barker Plateau and adjacent Shag Rocks Passage share a strong geological affinity with the Fuegian Andes and South Georgia, indicating a common geological history and no direct affinity to the Antarctic Peninsula. By contrast metasedimentary rocks of Bruce Bank from the South Scotia Ridge demonstrate a geological continuity with the South Orkney microcontinent and, also a geological affinity with the Trinity Peninsula Group metasedimentary rocks of the Antarctic Peninsula and components of the Cordillera Darwin Metamorphic Complex of Tierra del Fuego. Kinematic modelling indicates an Antarctic Plate origin for Bruce Bank and the SOM is the most plausible setting, prior to translation to the Scotia Plate during Scotia Sea opening.

Bering Strait gateway currents and effect on sediment distribution

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The Pacific Ocean has a one-meter higher dynamic height than the Atlantic Ocean. As a result, there is a strong geostrophic circulation north from the Bering Sea to Bering Strait where this entire water mass squeezes northward through an 80 km gateway to the Chukchi Sea. Coriolis force causes maximum currents of 250 cm/sec on the east side of the Strait (Fig 1). The northward increasingly strong current controls sediment distribution for 1000 km in the Bering Sea leading to the Strait, in the Strait, and north of the Strait in Chukchi Sea where currents slack.

Between St. Lawrence Island and the Yukon Delta 400 km south of Bering Strait, there is a wider (200 km) Sphanberg Strait gateway for the Alaska Current that flows northward toward Bering Strait (Fig. 1). Because both the Island and the Delta intrude into the northward current flow through this gateway, sedimentation in this area also is controlled by this gateway. Currents scour a moat on the eastern side of the Island and leeside sand bodies deposit on the eastern side of the Strait Figs 1, 2A). Leeside sand bodies develop when the northward geostrophic currents shear and accelerate against topographic projections into the current. When currents slack downstream, linear sand bodies deposit. Currents transport much of the local Yukon sediment from the Delta river mouth on the southwest corner, to deposit in the leeside sand body 30 to 100 km north of the River mouth (Fig. 2B).

From the Yukon Delta toward Bering Strait, the currents increasingly accelerate so that no Holocene sediment is deposited in Chirikuv Basin (Fig. 2). Instead a relict transgressive sand sheet of fine sand covers most of this 62,000 km^2 area. The sand sheet consists of a substrate rich in amphipods and clams that provide a major feeding ground for Pacific Gray whales and walruses. Their feeding pits and trails cover the Chirikuv Basin area, and are modified by currents that prevent sedimentation over them.

As the current accelerates closer to Bering Strait, 40 km south of the Strait, and continuing for another 40 km to the south, sand wave fields develop, where currents concentrate heavy minerals and heavy metals (e.g. cassiterite) in sand ribbons just south of the Strait (Fig. 1). On the American east side of the Bering Strait only shell lags over bedrock are found. When currents slack northeast of the Strait, a linear 140 km-long and 30 km wide leeside sand body is deposited (Fig. 2). This sand body is sourced by Yukon sand and sand from the Bering Sea beaches to the south of the Strait. When storm waves carry sand offshore from the Seward Peninsula beaches, it is transported through the Strait by the strong northward currents and deposited in the leeside sand body.

Storm surge setups in northern Bering Sea reach up to 5 m. Measured bottom return flows from a storm with a 1m storm surge setup show that 70% of the years sediment transport toward Bering Strait occurred. As a result of the common 1m storm surges and the several catastrophic 5 m setup storm surges per century, the majority of the Yukon sediment is carried through the Bering Strait gateway to deposit up to 1000 km north in Chukchi Sea. Evidence of this is shown by the up to 12 m of Holocene sediment in the southern Chukchi Sea (Fig. 2).

The economic implications of the Bering Strait gateway currents are concentrations of heavy minerals and heavy metals, the most important of which are the world's largest deposit of offshore gold near Nome Alaska. Because of the strong currents, the gold in relict gravels remain uncovered by Holocene sediment (Fig. 2). Moreover, the formation of massive leeside sand bodies are analogues for potential petroleum reservoirs in epicontinental shelf petroleum systems.

Figure 1. Currents related to the Bering Strait gateway

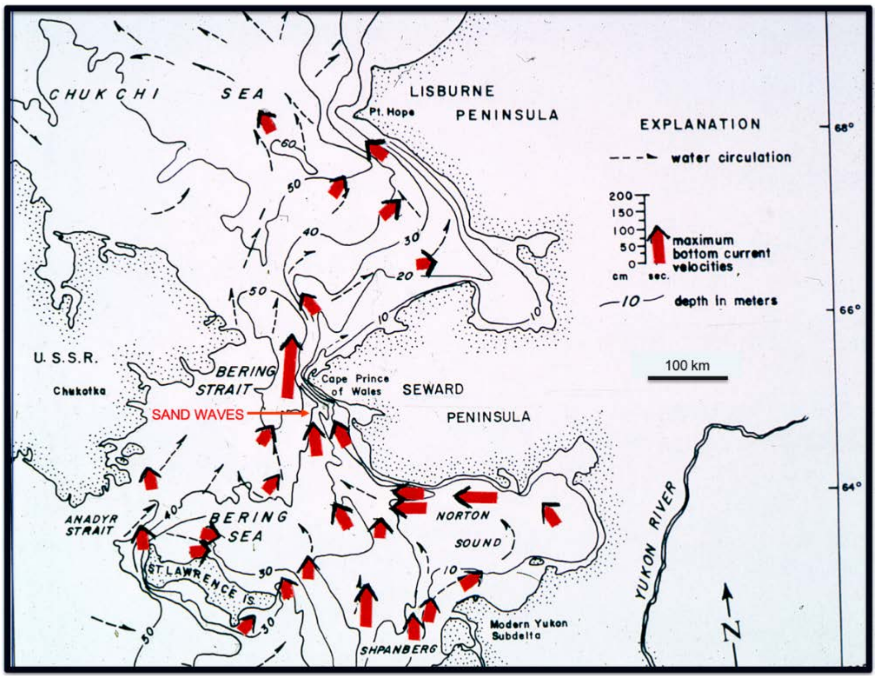
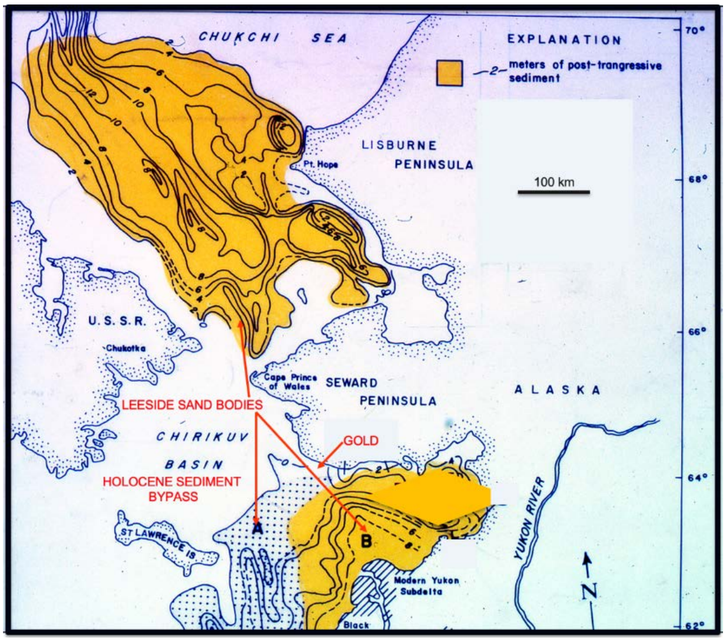


Figure 2. Holocene Yukon deposits (yellow) related to Bering Strait gateway



Timing and consequences of Bering Strait oceanic gateway opening: New insights from $^{40}Ar/^{39}Ar$ dating of the Barmur Group (Tjörnes beds), northern Iceland

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The Barmur Group (informally the Tjörnes beds) of northern Iceland is key to reconstructing the first opening of the Bering Strait oceanic gateway because these rocks record migration of bivalve molluscs from the Pacific to the Atlantic via the Arctic. However, the timing of this faunal migration event is poorly constrained owing to lack of reliable absolute ages. To address this problem, we present the first $^{40}Ar/^{39}Ar$ radiometric dates from four basaltic lavas that underlie, are intercalated with, and overlie the Barmur Group, and integrate the dates with existing palaeomagnetic records.

Pacific bivalve molluscs first appeared in the Barmur Group during sub-chron C3n.3r at 4.997–4.896 Ma, over 1.4 million years earlier than in previous age models. Appearance of Pacific bivalves in the northern Atlantic is contemporaneous with the 4.8–5.5 Ma age for Bering Strait opening inferred from bivalve-bearing successions in the Pacific and Arctic Oceans next to the gateway. Thus, our data refute a hypothesized two-stage trans-Arctic faunal exchange process spanning c. 2 million years, and instead imply a single episode of bidirectional faunal exchange at or soon after first opening of the Bering Strait gateway. Our results also confirm that first opening of the Bering Strait gateway was not directly associated with growth of large northern hemisphere icesheets, which occurred several million years later.

Our new age model shows a latest Miocene to early Pliocene range for the Barmur Group (c. 6.0−4.4 Ma; between C3r and C3n.2n), older than all previous age models. The Barmur Group has been suggested to record the mid-Piacenzian Warm Period (mPWP; c. 3.2 Ma), the most recent geological period when atmospheric carbon dioxide concentrations were similar to present, and surface temperatures were as predicted for the coming century. Our new ages model supports the removal of Barmur Group-derived data from recent versions of the PRISM database, which is used to reconstruct global climate during the mPWP.

Keynote – Neil Hodgson and Karyna Rodriguez

Gateways: The Contourite context

Over the last decade there has been a growing recognition that the sedimentology of deposits formed when contour parallel currents interact with gravity driven systems is super-important to energy explorers.

Oil and gas still play a role in the transition from low carbon to zero carbon energy. Deep water is where the last giant prospects lie and where such resources can be most commercially explored and developed. Modern deep-water seismic data show that Contourite deposits are incredibly common in in deep water settings, and I suggest that the role of contourites in shaping gravity driven systems has been grossly misrepresented, possibly due to the mismatch of scales of outcrop and seismic datasets.

Contourite mixed system thinking not only offer a better model of deep-water clastic plays, which becomes key in effective development of deep-water reservoir they can offer new plays, new trapping styles and new sand cleaning and ponding systems offering better predictive analysis.

Into this important discussion comes the phenomena of gateways opening as continents fragment - these gateways changing and switching on or off contourite currents patterns. These basin wide events provide correlative geometries which can be used in the absence of other data as a stratigraphic correlation tool.

The understanding of the timing cause and effects of gateways on contourite currents is critical to the interpretation of basin scale seismic and the prediction of all key risk elements of basin play evaluation.

In the next 10 years contourite and mixed system plays will become the dominant giant play type for the industry - so the understanding of gateways becomes the stage on which the future of man’s energy supply through the transition are played out.

Entrapment and expansion of water masses in oceanic gateway-related environments and its implication for the birth of source rocks: sedimentary geochemistry from the Permian and Aptian/Albian Gondwanan geological record

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Paleooceanic gateways were pivotal in the development of past epicontinental seas since they controlled water masses exchanges between the open ocean and restricted environments. Narrow marine connections, associated with the inland context, may have been determinant in driving primary bioproductivity and organic carbon burial, which makes the study of these restricted environments particularly important in the context of source rocks. In this sense, to understand the processes that controlled the generation of organic matter-rich sediments at times of closing and opening of paleooceanic gateways, we report newly obtained geochemical data (TOC-total organic carbon, Rock-Eval, and stable organic carbon and nitrogen isotope analysis) for the Permian interval from the Karoo Basin (Whitehill Formation-DP1/78 borehole) and Aptian-Albian of the Parnaíba Basin (Codó Formation/1-PI-UN-25-PI borehole). Such an evaluation will allow, within the framework of already existing data, to assess and compare the processes related to the birth of the source rocks at times of closing and expansion of an oceanic gateway, related to the demise of the Irati-Whitehill sea and to the first marine incursions in the context of the opening of Gondwana (Bastos et al, 2021;2022).

For the Whitehill record (DP1/78 borehole), the heavy $^{13}C_{org}$ values (-17‰) in shales presenting TOC of around 10% suggests that microbial expansion processes were pivotal for the generation of the sedimentary organic horizons and that these processes occurred both in regions closer to and farther from the oceanic entrance gateway (Faure and Cole, 1999; Bastos et al, 2021). TOC contents lesser than 10% and d^{15}N values between 2.8‰ and 7‰ suggest moderate salinity conditions where processes of ammonia volatilization and/or nitrification inhibition were not as significant (Wei et al, 2021). These conditions are consistent with the paleoreconstruction of the main southern oceanic gateway and the paleogeography of the Irati-Whitehill sea in the context of the studied section.

For the record associated with the opening of the South Atlantic Oceanic northern gateway, the Aptian-Albian record (Codó Formation) shows elevated TOC values (reaching 16%). The high hydrogen index content (~650mgHC/gTOC) in these samples suggests, however, that there was a large contribution of marine organic matter possibly related not only to the seaway opening context but also to the Cretaceous climate conditions. The elevated TOC values recorded in the Codó Formation are not associated with the more negative $^{13}C_{org}$. values. This condition could imply a climatic depositional control. The expansion of the marine realm allowed the establishment of marine gastropods that are mapped in the main northeastern Brazilian basins that were adjacent to the paleoceanic gateway. Finally, the evolution of the oceanic gateway coupled with climate drove marine incursions toward Brazilian southeast basins resulting in a progressively stronger marine influence with the development of enormous salt deposits and, further, open marine record (e.g Campos and Santos Basin-Davison, 2007).

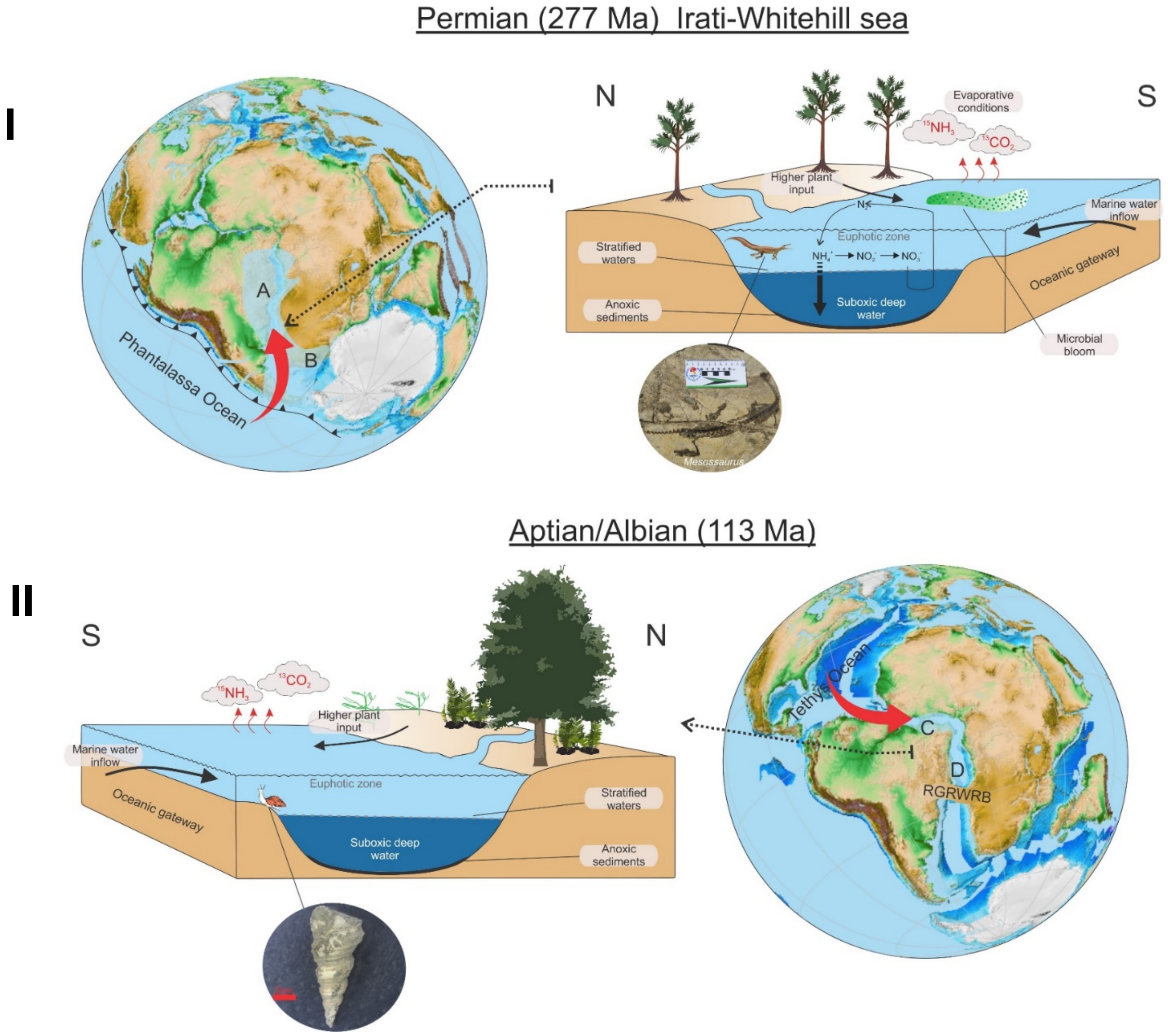

Figure1) I-Paleogeographic reconstruction of the Irati-Whitehill sea showing the Paraná and Karoo basins indicated in the map (A and B, respectively), and the main processes related in the generation of the organic-rich sediments. II-Paleogeographic reconstruction of the first Gondwanan marine Cretaceous ingressions with the studied Parnaiba Basin indicated in C and the southeast Brazilian basins in D. RGRWRB- Rio Grande Rise and the Walvis Ridge.

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Sedimentology and ichnology of Upper Jurassic to Lower Cretaceous contourites in an unconventional shale reservoir (Vaca Muerta Formation, Argentina)

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The Upper Jurassic to Lower Cretaceous Vaca Muerta Formation (Neuquén Basin, Argentina) is one of the most prolific unconventional shale reservoirs in the world, being exploited since more than a decade (Minisini *et al.*, 2020). This formation is composed by mixed carbonate-siliciclastic, fine-grained clinoforms and its deposition was affected by severe anoxia. A sedimentologic and ichnologic analysis has been performed in cores from eight wells (940.5 m total) and one outcrop (148 m thick). Four types of deposits have been differentiated, such as marginal marine, basin, contourite drift, and slope. The contourite drift deposits (44 m total) are constituted by crinoidal mudstone, and mixed and calcareous mudstone showing parallel lamination, low angle cross-lamination, current-ripple cross-lamination, and cross-bedding, alternating with intervals displaying high intensity of bioturbation. Locally, m-thick successions showing decreasing to increasing bioturbation index occur. The ichnofauna consists of *Crininicaminus* isp., *Lockeia siliquaria*, ?*Lockeia* isp., *Nereites* isp., *Palaeophycus* isp., *Palaeophycus heberti*, *Phycosiphon incertum*, *Planolites* isp., ?*Skolithos* isp., and escape and equilibrium trace fossils. Several lines of evidence suggest that these deposits were produced by semi-permanent bottom currents. (1) The scarcity of normal-graded or bioturbated caps, the high hydrodynamic energy stress on the benthos in the middle of the decreasing to increasing bioturbation index successions, and the existence of suspension feeding trace fossils (*Lockeia* and equilibrium structures) indicate bottom currents with semi-permanent activity. (2) The numerous traction structures points towards a flow of low sediment concentration, capable of sediment transport in the low angle slopes of the clinoform system (0.2-0.3º). (3) The intensely bioturbated intervals indicate sustained, long-term oxygen introduction by currents, which contrasts with the typical oxygen-deficient basin deposits of this formation. The present study suggests that fine-grained contourites may preserve traction structures when stress factors are combined (hydrodynamic stress and dysoxia) and supports the idea of increased oxygenation associated with contourite transport. Contourite drift deposits were dominant during regressive conditions, associated with increased carbonate and bioclastic production in the clinoform topset. In turn, carbonate deposits were dominant during arid and cool climate periods (Brysch, 2018; Alberti *et al.*, 2020). Therefore, it is hypothesized that weakened estuarine to anti-estuarine circulation associated with cool climates triggering enhanced cascading from the South (Rodríguez Blanco *et al.*, 2020) may have intensified the contour current system and produced the drift deposits analyzed. These deposits show considerably high TOC content (av. 3.55%, N=11), and are coeval with basinal units poorer in bioclastic content but richer in TOC (up to 10-15%, Minisini *et al.*, 2020). The latter represent the typical target for hydrocarbon development, whereas the former might be future secondary targets. The present combined sedimentologic and ichnologic analysis improved the understanding of sedimentary processes and environmental conditions during the deposition of the Vaca Muerta Formation and will help to refine models for hydrocarbon exploration and development in the future.

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The contourite depositional systems in the offshore basins of Sulawesi and its implication to reservoir distribution

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Sulawesi Island play important roles in the Indonesian Throughflow (ITF) transports water from the Pacific to the Indian Ocean. Pacific Ocean water moves around Sulawesi along the Sulawesi Sea, Makassar Strait, Lifamatola Strait, Flores Sea and Banda Sea into the Indian Ocean. Offshore basins in Sulawesi are connected by these gateways and record key information concerning the effects of tectonic activity and deep marine sedimentation including turbidity and bottom currents. Numerous studies have been conducted to understand the complex geology of Sulawesi. However very little study on the bottom-water circulation that is crucial in redepositing and reworking clastic materials.

Combined analysis of bathymetry, well, and seismic data reveal that sedimentation in offshore basins of Sulawesi is strongly influenced by deep- and bottom-water circulation. There are 3 major contourite areas that are observed in this study. Contourite depositional system in these basins has been fed by the Celebes Molasse sediments since the Neogene. The eroded syn-tectonic Celebes Molasse sediments have been subsequently deposited as contourites in a thick sediment drift along the steep slope of the Manui, Bone and Lariang basins. The development of the CDS has been controlled in general by the Miocene and Plio-Pleistocene unconformities and by the steep morphology of the basin margin. The influence of contour currents on the steep-slope sedimentation can be significant and proves invaluable bottom current reworked sand (BCRS) as future reservoir targets.

The influence of bottom current circulation in offshore Sulawesi is relatively understudy and is worth as a new reservoir target for hydrocarbon exploration. The main depositional features are characterized by sedimentary wave fields, infilled contourites channel, mixed drifts, plastered drifts, elongated mounded, separated drifts, sheeted drifts and sand dunes. The main erosive features are contourite channels, furrows, scouring surface and moats. Petrophysical characteristics of CDS sedimentary facies shows in Sampolakosa well with porosity ranging from 15%-22% as promising reservoirs. Five formations have been identified to contain CDS, which from east to west are: Unit B, D, E in Bone Basin, Pasangkayu Fm in Lariang Basin, Walanae Fm in SW Sulawesi, Langkowala Fm and Boepinang Fm in SE Arm Sulawesi.

Keywords: Contourites, molasse, reservoir, bottom current, ITF

Hydrocarbon Potential Seismic Evaluation of Hybrid Turbidite Contourite Systems

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Introduction

In deep water settings along continental margins, mixed systems where coast parallel bottom currents and gravity processes interact are common. The interaction of these processes can build large mixed / hybrid (turbiditic-contouritic) depositional systems. We have just begun to explore in sufficient water depths to access hydrocarbon plays in these systems and they are already associated with some of the most major recent global discoveries.

Key examples of prolific discoveries associated with hybrid turbidite-contourite systems, include the Rovuma Basin offshore Mozambique (Mamba Complex 85 TCF) (Palermo et al., 2014), the Jubilee Field and TEN fields offshore Ghana (Cronin, 2018), the deep water confined channel Barra complex (3 BBOIP) in the Sergipe Basin, Brazil, the Orca, Yaakar and Tortue Fields (15 TCF) offshore Mauritania (McGuinness et al., 2021) and the most recent addition to the list, Graff-1 offshore Namibia (3 BBOE) (Bijkerk et al., 2021).

This study focuses on recognizing and evaluating mixed systems on seismic data, including examples from offshore Mexico, Peru, Brazil, Argentina and South Africa.

Seismic identification of mixed turbiditic-contouritic depositional systems

The identification of hybrid systems relies on the recognition of a series of diagnostic criteria derived from the integration of available understanding of these mixed systems (Sansom P., 2018). Contourite drifts are some of the easiest features to identify. They can be either mounded when they can be of giant size or isolated, nested, slope leveed or sheeted (plastered, or abyssal). Drifts are commonly comprised of silt or shale and represent the resting place for the fine-grained material shed into a basin. However, what we don't see so easily on the seismic section is the high grading of clastic sediments by winnowing of fine material from turbidity currents. To deduce the possible effect of these we need to look for the channels that move against the current, driven by contourites building levees down dip (Figure 1).

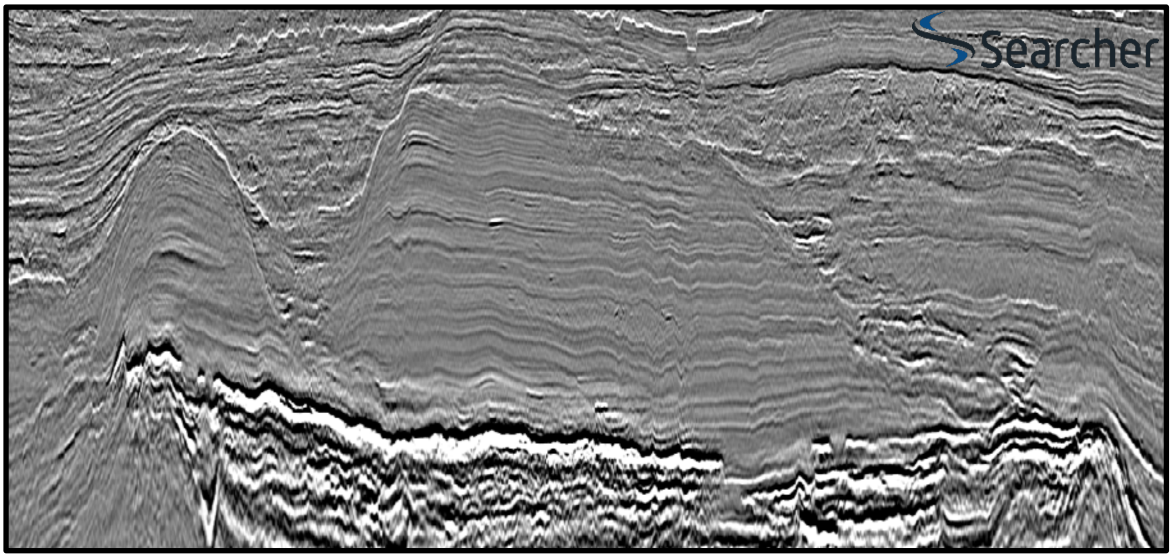

Figure 1: Offshore Mexico, a contourite current is interpreted to interact with a turbidite flow whilst it's running down the slope, stripping away the cloud of fine mud in the flow with which it builds the giant contourite drift (2km high by 20 km wide), leaving high net/gross sands behind indicated by the high amplitude anomalies within the channel

axes. The action of these latter currents in a constructional slope setting forces the channel to migrate laterally, setting up traps and seals (Palermo et al., 2014).

Hybrid Turbidite Contourite Systems Seismic Examples

In recent years the availability of high-quality regional scale seismic images has drawn attention to the frequent presence of contourite dominated bedforms and several recent notable discoveries in contourite dominated sequences have required a re-evaluation of the importance of contourites influence on deep water exploration models. Using an enhanced seismic global dataset, several systems have been recognized which remain undrilled but largely de-risked by recent discoveries which provide successful analogues.

Contourite currents are not constant in time and in-fact are not even constant down any given slope. The first condition – reflecting changes in the way oceans communicate – the opening of gateways between continents, climate variations or even weather systems and atmospheric CO2, means that sequences in undrilled basins that display contourite behaviour of a given character may be correlated. The second condition – reflecting cells of the ocean that do not mix, and have different density with depth, means that you have to be very careful that you are correlating isopichnally similar units on a given slope.

Conclusions

Mixed/Hybrid turbiditic-contouritic systems are just beginning to be understood and recognized in major discoveries at a global scale. Modern 2D seismic is proving to be an essential tool in identifying these systems and performing a hydrocarbon potential evaluation. The huge potential already proven offshore Mozambique, Ghana and Sergipe indicates that hybrid plays will be the main target in deep water exploration. Examples from Mexico, Peru, Brazil, Argentina and South Africa, all indicate that the potential is very extensive, implying that this system should be considered as a viable highly prospective future target

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POSTER ABSTRACTS

Bottom-current morpho-sedimentary features of the Messina Strait

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The Messina Strait (Fig. 1) is a narrow (~ 3-8 km wide) gateway that connects the Tyrrhenian Sea with the Ionian Sea (Mediterranean Sea). It is characterized by a shallow sill (~-110 m deep) and steep margins (> 10° on average) dominated by downslope processes (e.g., sedimentary gravity flows forming slope channels and coarse-grained aprons), favored by intense tectonic activity, seismicity, steep gradients and high sediment input from water courses. The Messina Strait is known worldwide for its strong (~ 3 m/s) reversing tidal currents, characterized by a northward flow of the Levantine Intermediate Water (LIW) and a southward flow of the Tyrrhenian Surface Water (TSW). These flows strongly interact with the irregular seabed morphology of the Strait, determining complex and vigorous hydrodynamic conditions (e.g., convergence of currents, turbulent structures, internal solitary waves).

In this work we investigate the main bottom-current morpho-sedimentary features deciphered by the analysis of an extensive dataset of high-resolution multibeam bathymetry. A suite of large (several kilometers) to medium (tens to hundreds of meters) scale erosive and depositional features, related to different bottom-currents (e.g., reverse tidal flows, residual flows, internal waves) acting over diverse time periods, are identified.

Large scale bottom-current features are represented by contourite drifts (e.g., elongated drifts and channel-patch drifts) and channels (e.g., various moat channels and the Scilla Channel running on the northern exit of the Strait; SCh in Fig. 1), developed over long time periods (e.g., > thousands of years). Medium-scale features include scours, furrows, transverse ridges (pinnacles) and narrow longitudinal bodies in the sill sector and several sand wave fields, located on the Ionian and Tyrrhenian sides of the Strait, formed during shorter time periods. Locally, a clear interaction between bottom-currents and downslope processes can be observed (e.g., obstacle marks related to the M Pacì landslide deposits in the Scilla Channel).

Based on the characteristics of the morpho-sedimentary features, the main patterns of bottom-current directions are reconstructed, at both the large and medium spatial scale. Moreover, the recognition of a variety of erosive and depositional bottom-current morpho-sedimentary features highlights different links with the various hydrodynamic processes of the Messina Strait. Main examples are: a) the formation of the Scilla Channel (SCh in Fig. 1) that is likely related to the long-term action of the north-directed LIW outflow, b) the formation of the Capo Peloro Drift (CPD in Fig. 1) possibly related to the long-term interaction between the main LIW branch, flowing along northern slope of Sicily, and the outflow of the MS, c) the formation of the offshore sediment waves field (OS in Fig. 1) on the northern slope of the Capo Peloro Drift seem to be associated to a divergent pattern of north-ward directed bottom currents possibly induced by internal solitary waves.

Although more information (e.g., seismic profiles, sediment cores and mooring measurements) is needed to shed light on the accurate correlation between the observed morpho-sedimentary features and bottom currents, results from this study provide insights for interpreting similar features in modern and ancient straits.

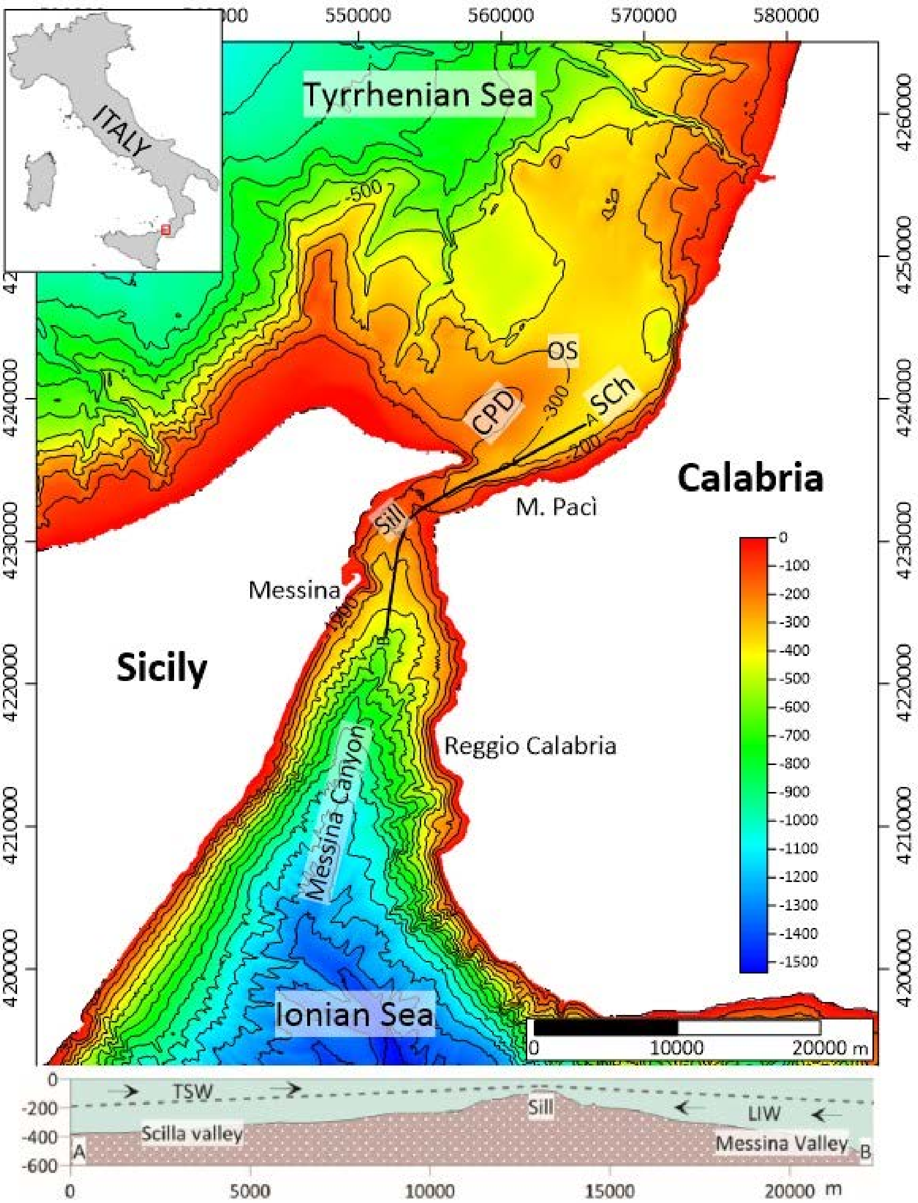

Fig. 1. Multibeam bathymetry of the Messina Strait and bathymetric profile with a sketch of main water masses (TSW and LIW) crossing the Strait (lower panel); SCh: Scilla Channel; CPD: Capo Peloro Drift.

Facies-based tidal strait model and implications for interpreting ancient gateways

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Observations of the sediment distribution and hydrodynamics among a number of modern and ancient tidal straits have strengthen the framework of their general depositional style and facies distribution (e.g., Longhitano, 2013; Longhitano & Chiarella, 2020; Dalrymple, 2022).

The sedimentary dynamics of tidal straits is dominantly related to the virtually continuous bi-directional currents, secondarily to waves and other types of water movements. Tidal flows reach their peak velocity in proximity of zone/s of lateral constriction or extreme shallowing, exerting prevalence erosion and scouring of the strait floor. Currents loose progressively their energy and transport capacity where they encroach larger zones of a strait, leading to sediment deposition and the development of a variety of bed features. A possible four-fold partition of straits into discrete sedimentary zones based on the observation of several modern and ancient examples, reveals common physiographic elements, oceanographic similarities and comparable facies. This zonation includes: (i) the strait-centre zone, associated with the tidal current maxima and where sediments are scarce or absent; (ii) the dune-bedded zone, where sediments accumulate into bedform complexes due to tidal flow expansion; (iii) the strait-end zone, where currents decelerate generating thinly-bedded, fine-grained facies; (iv) the strait-margin zone, where marginal-marine deposits, associated with mass flow strata along steep margins, merge with tidal deposits.

In straits with a marked asymmetry between the two reversal tidal currents or undergoing to unidirectional non-tidal flows, this facies-based partitioning is still valid, but with a single (rather than double-specular) major depositional area located down current with respect to the main regional sediment transport.

Although based on modern and ancient case studies situated in shallow-marine (i.e., less than 500 m deep) settings, the four-folded tidal strait model can be considered as depth independent. Hydrodynamic conditions related to oceanic currents, with or without bi-directionality, may also occur in deeper (1,000 m deep) settings. These local passageways may be common in oceanic gateways and seaways, which are 1,000 km-wide systems larger than straits. Straits may be the ‘hidden engine’ for the propagation of deep-water flows and their consequent climatic influence into adjacent subaqueous sectors of wider gateways. A modern example is the Sicilian gateway in the central Mediterranean (e.g., Reeder et al., 2002), whereas an ancient case study can be represented by the late Miocene connection between the Atlantic and the western Mediterranean (Krijgsman et al., 2018). In both these gateways, internal straits are due to local, tectonically induced constrictions that influence deep-water exchanges and propagation.

The consideration that gateways and seaways of the past have included internal paleostraits has important implications, among others, on: the local amplification of currents and consequent spatial distribution of facies; (ii) development of other deep-water systems, including turbidites and contourites; (iii) the reconstruction of the regional-scale paleoceanography.

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Echo-character distribution with respect to bottom current pathways in the Western Gap (Azores—Gibraltar Fracture Zone, NE Atlantic)

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Bottom currents may be considerably altered when they encounter topographic obstacles. In these areas, there may be mixing of water masses and an amplified erosive-depositional effect where currents are topographically restricted by deep gaps or deep gateways. In the deep-sea environment these gaps connect two adjacent abyssal plains and, thus, contribute to the exchange of biota, sediment, and deep water masses between separate abyssal plain environments. However, due to the remoteness of these areas, it has proven difficult to build a complete picture of the processes associated with bottom currents.

Here, we use bottom current pathways determined from previous studies of hydrological data acquired in 2021 and the results of numerical modelling in the Western Gap in the Azores–Gibraltar Fracture Zone, NE Atlantic (Fig. 1). To discuss the erosive and depositional implications of these bottom currents, we used echosounder data and seafloor videos acquired during the same cruise to build morpho-sedimentary and echo-character distribution maps of the area.

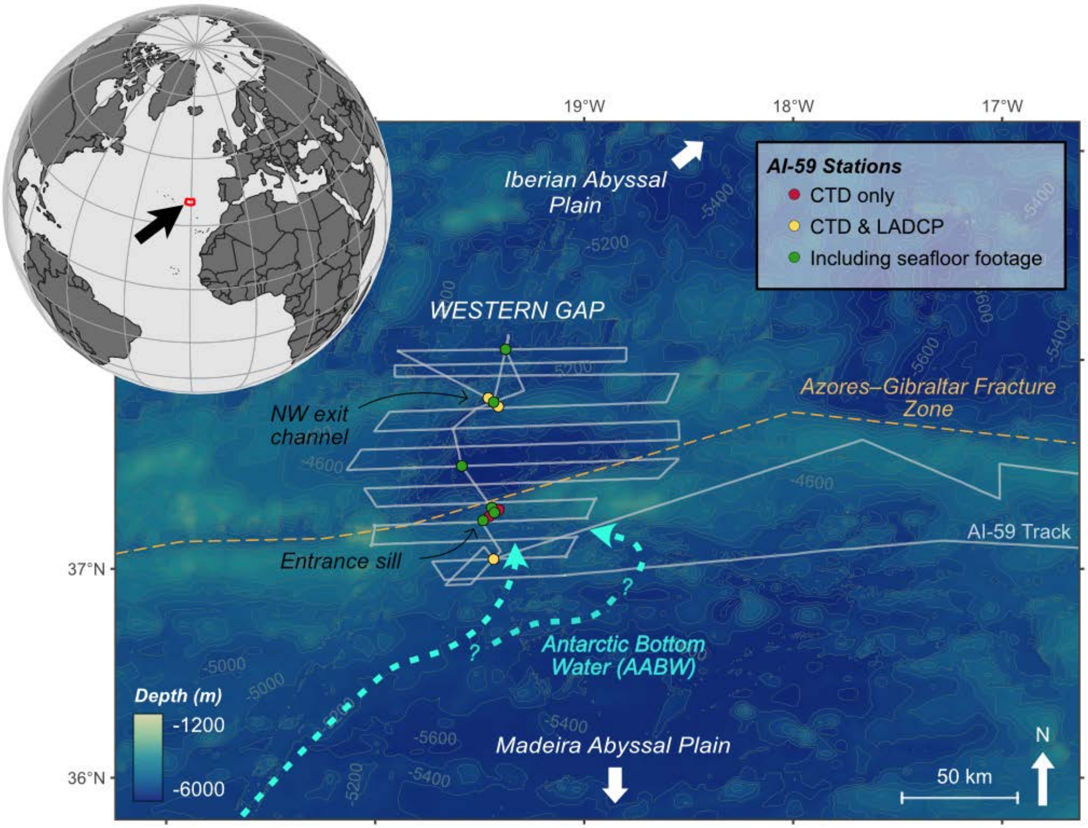

Figure 2: Location of the study area in the NE Atlantic. Sub-bottom surveying followed the marked cruise track line. Possible pathways of the two branches of Antarctic Bottom Water (AABW) that are found at the entrance sill of the Western Gap are shown with the blue dashed lines.

We divided the study area into 5 areas: the north-western part of the Madeira Abyssal Plain, the entrance to the Western Gap, the interior basin of the gap, the NW exit channel of the Western Gap, and the south-western Iberian Abyssal Plain (Fig. 1). We found that while bottom current velocities in the two abyssal plains were low and echo-types reflected low sedimentation rates, there was also evidence of greater erosion in the Western Gap as indistinct and hyperbolic echoes.

Bottom water with potential temperature <2 ˚C, determined to be Antarctic Bottom Water (AABW), enters the Western Gap from the south as two branches below 4865 m over the entrance sill with a measured velocity in the near bottom layer of >28 cm/s directed north, exceeding modelled velocities of ≲10 cm/s. The measured velocity and orientation are also in agreement with the formation of observed sedimentary waves, scours and comet structures at the entrance of the Western Gap which may be due to pulses of very high energy flow, potentially over 50 cm/s at times. It's possible that one branch of the water is deflected to the east within the Western Gap. Echo-type distribution indicates greater erosion along the eastern flanks of the gap compared to the western flanks, and numerical modelling also demonstrates increased bottom current activity to the east, further supporting this hypothesis.

The distribution of echo-types and measured current velocities may suggest that the Western Gap is currently, or has previously been, a major gateway for AABW into the Iberian Abyssal Plain from the Madeira Abyssal Plain. Hence, the constructed sediment distribution maps can further improve our understanding of bottom current pathways in the NE Atlantic and the erosive-depositional potential of bottom currents as they pass through deep marine gaps and gateways.

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Contourites in the eastern part of the Vema Fracture Zone (Tropical Atlantic)

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Contourite drifts in the abyssal realms of the Atlantic keep the record of the activity of the Antarctic bottom water (AABW) which is an important part of the Atlantic meridional overturning. The distribution of the AABW in the Atlantic occurs through a series of deep-water passages (e.g., Vema Channel, Romanche fracture zone). The drifts (and contourite depositional systems) related to these oceanic gateways are key areas to study of AABW history and impact on sedimentation (Masse et al., 1994; Ivanova et al., 2016, 2021, 2022; Sivkov et al., 2019; Glazkova et al., 2022). The Vema Fracture Zone (FZ) plays a crucial role in the AABW propagation from the Western to Eastern Atlantic. Despite of the intense AABW net flow through the FZ and high sediment input, there is a lack of unambiguous evidence of contourite occurrence in the area. Furthermore, it is generally accepted that the sedimentation within the Vema FZ is mainly controlled by gravity flows (at least during the Pleistocene) (Benson et al., 1970; Perch-Nielsen et al., 1977).

The high-resolution sub-bottom profiling carried out in the Vema FZ between 40°W and 38°40'W (RV Akademik Ioffe, cruise 60, 2021; Fig 1A, B) revealed two mounded drifts separated from the steep southern wall by moats (Ivanova et al., 2022). Within the region studied, the width of the valley varies from 1.5 to 9 km. Two elliptic sediment-filled areas (9 x 40 km and 9 x 70 km), bounded by narrow (1.5 - 2 km) passages without sediment cover are identified (Fig. 1B). The water depth exceeds 5200 m. The seismic structure of the upper 50 m of the sediment cover in the study area is characterized by intercalation of acoustically transparent and stratified units (VU1-4) separated by discontinuities (Fig. 1C, D). The uppermost unit (VU-4) is transparent and lies oblique to the top of the lower stratified unit (VU-3). Within the stratified unit a moat and related drift deposits are identified. The drift deposits display slightly upslope progradational reflector configuration with onlapping and downlapping terminations of individual reflectors upon the discontinuities bounding the unit. The discontinuity marking the unit base truncates the reflectors of the two lowermost units which do not show any clear diagnostic features of current-controlled depositions. Two drift – moat systems are found in both elliptic areas. These systems are linked to the eastern exits from the narrow passages. Moats are 10 m in depth and up to 3 km in width. They extend for 25 and 35 km, respectively, along the southern boundary of the valley. Mounded elongated drifts have a width of up to 8 km and thickness up to 60 m. The intercalation of transparent and stratified units probably reflects changes in sedimentation mode in response to eustatic sea-level changes (transparent units - sea-level rises, stratified – sea-level drops). The evidence of current-controlled sedimentation was revealed only in unit VU-3. The burial of drifts and moats under acoustically transparent deposits suggests the modern inactivity of these contourite systems. The speed of the eastward flowing AABW current has to increase in the narrow passages. The Coriolis force pushes the flow to the southern wall. This explains the location of the drifts and moats in near the eastern exits of the narrow passages (Fig. 1B).

The sub-bottom profiling (RV Akademik Ioffe, cruise 60, 2021) in the area between spreading ridge segments did not confirm the presence of sediment waves described by Kastens et al. (1986). The recorded hyperbolic echos correspond to the principal transform displacement zone.
The revealed contourite features shows the significant impact of the bottom currents on the formation of the upper part of sediment cover and points to the incompleteness of the current paradigm of the Quaternary sedimentation in the area.

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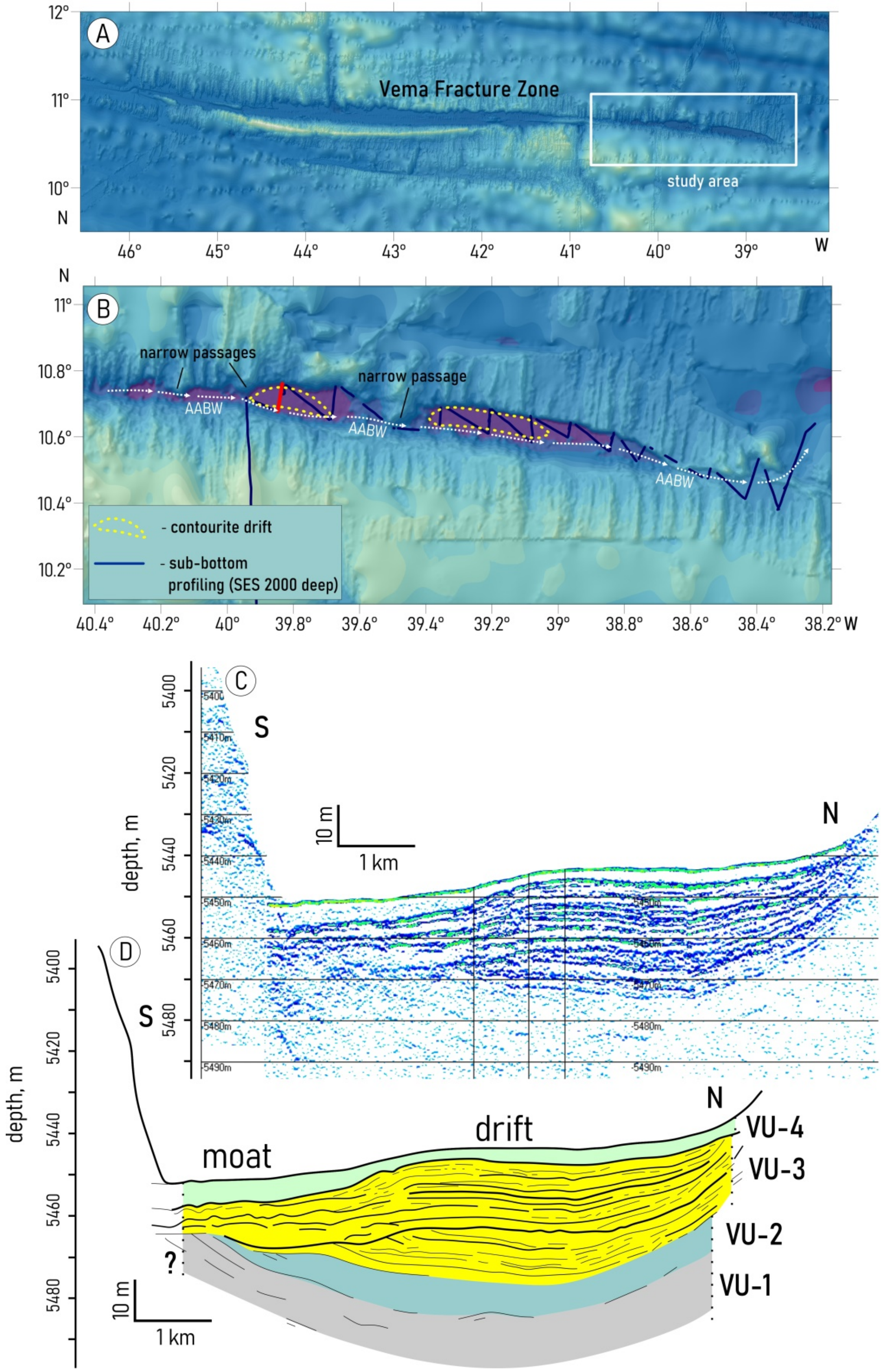

Fig. 1. A) The location of the study area (based on GEBCO 2021); B) The bathymetry of the study area with location of sub-bottom profiling lines and drifts, arrows indicate general direction of bottom currents. Red line marks the location of the profile shown in Fig. 1C; C) The record collected using SES 2000 deep parametric echo-sounder; D) The interpretation of the sub-bottom profiling record.

Deep-sea terrigenous and biogenic calcareous contourite systems around the northern exit of the Vema Channel

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The Vema Channel is known to play a key role in the modern thermohaline circulation, providing the major pathway for the northward flow of Antarctic waters, as well as for the southward input of North-Atlantic Deep Water. This is apparently also true for the past, at least since an appearance of the Atlantic meridional overturning in the Oligocene. Bottom currents of the southern and northern origin, in turn, created the contourite depositional systems (CDSs) of different scales in the SW Atlantic. During nine scientific cruises of the RV Akademik Ioffe in 2010 – 2017, a series of contourite drifts, sediment wave fields and erosional contourite features are identified near the northern exit of the Vema Channel, in particular the dominantly calcareous Ioffe Drift overlying the Florianopolis Fracture Zone (FFZ) ridge. These morphological features provide suitable sites to examine past variations in bottom current speed, direction, and their contribution to the CDSs formation. The study of collected materials is based on two main approaches, notably an interpretation of high-resolution sub-bottom (seismoacoustic) profiling and a multidisciplinary investigation of fourteen sediment cores. Two regions to the west-northwest and northeast of the Vema Channel, respectively, have been studied in detail: (1) the Santa Catarina Plateau – São Paulo Plateau area, and (2) the Ioffe Drift.

To the west, an anticyclonic gyre of Lower Circumpolar Deep Water (LCDW), created from the westward branch of the Vema Channel outflow, is instrumental in the development of contourite drifts and sediment waves in the Santa Catarina Plateau – São Paulo Plateau area. The contourite origin of generally silty terrigenous Middle Pleistocene to Holocene sediments is ascertained by both morpho-seismic and sedimentary characteristics. The core lithology is characterized by a lack of primary sedimentary structures and pervasive bioturbation, sharp erosional contacts, local hiatuses and stiff mud horizons, some sandy/silty layers and indistinct bedding, mostly fine grain-size, very poor sorting, distinctive bi-gradational sequences up to silty sand and sand size, a high degree of correlation between the sortable silt (SS) content in the total <63 µm size fraction and SS mean sizes in all eight cores studied, and a mixed terrigenous-biogenic composition, reflecting part hemipelagic input and part downslope sediment supply.

To the NE of the northern exit from the Vema Channel, in the Ioffe Drift area, another anticyclonic gyre from the main LCDW branch, following northeastward along the FFZ, controlled extensive erosion and reworking of contouritic sediments, as well as their lateral transport and accumulation. The drift is far from any source of terrigenous material and deposited in an area of low biological productivity in the pelagic realm of the South Atlantic. The overall morphology, seismic structure of the upper sediment cover, and occurrence of internal unconformities along with the sediment characteristics including common hiatuses (corresponding in some cases to erosional contacts), pervasive bioturbation, generally poor sediment sorting, and more or less well-developed bi-gradational sequences document the drift’s contourite origin. Extensive erosion by bottom currents has created numerous hiatuses and markedly reduced the thickness of the Upper Pliocene – Quaternary succession of stratigraphic zones in the drift area.

Thus, both mostly terrigenous (mixed composition) and calcareous (biogenic) contourites documented from the study areas are characterized by the occurrence of erosional contacts and hiatuses, layering (in some cases), pervasive bioturbation, mostly poor to very poor sorting, and more or less well-developed bi-gradational sequences. The degree of correlation between content and mean size of SS in the fraction <63 µm as well as average sedimentation rates are higher in terrigenous contourites as compared to biogenic calcareous ones. The results of the study are mostly published in (Ivanova et al., 2016, 2020, 2022) and in the monograph (Murdmaa and Ivanova (Eds.) The Ioffe Drift. Springer, 2021). This presentation is a contribution to the Russian Science Foundation project 22-27-00421.

Late Miocene to Quaternary bottom current deposits in the Gulf of Cadiz related to the Mediterranean - Atlantic exchange evolution: decoding bottom currents behaviour and oceanographic processes associated with gateways

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Contourite depositional systems represent the sedimentary records of paleoceanographic circulation and paleoclimatic changes throughout the geological timescale. These records offer expanded but contingent information relative to their adjacent gateways, documenting changes in the intensity and the direction of modern-day and paleo-current pathways on multi-centennial, millennial and million-year timescales. This study investigates the late Miocene to Quaternary sedimentary record in the Gulf of Cadiz after the exit of the Strait of Gibraltar, a key gateway for the Mediterranean – Atlantic exchange. A summary of the key results is presented as a representative study case for decoding the long- and short-term behaviour of bottom currents and oceanographic processes related to gateways and their associated overflows.

In the study area, it is well known that the Mediterranean Outflow Water (MOW) has generated a complex contourite depositional system since the opening of the Strait of Gibraltar at the beginning of the early Pliocene (5.3 Ma). Recently, an ancient contourite depositional system has also been characterised for the late Miocene, which is separated from the Pliocene-Quaternary system by a period of quiescence representing the restriction of bottom water circulation across the Mediterranean-Atlantic exchange during the latest Messinian (~6.4 - 5.3 Ma, Fig. 1). The late Miocene contourite depositional system was established after the final closure of the Indian Gateway (IG) and the Neo-Tethys Ocean in the Middle Miocene (Fig. 1), followed by the inception of the Mediterranean Sea (from ~13.8 to 11 Ma). The final closure of the Indian Gateway conditioned a wide gateway connection between the Mediterranean Sea and the Atlantic, with the full establishment of an anti-estuarine circulation similar to the present day as opposed to its previous situation.

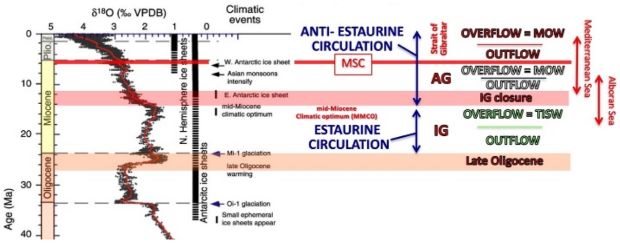

Figure 1. Summary of the Mediterranean - Atlantic exchange because gateways evolution. The Late Miocene and Pliocene-Quaternary contourite depositional systems are separated by a period of restriction in that exchange during the latest Miocene (6.4-5.3 ma) including the Messinian Salinity Crisis (MSC, 5.97 - 5.33 Ma). Isotopic curve from Zachos, *et al*., 2001. *Abbreviations:* AG= Atlantic Gateway; IG= Indian Gateway; MOW= Mediterranean Outflow Water; MSC= Messinian Salinity Crisis; TISW= Tethyan Indian Saline water.

Interestingly, both the late Miocene and the Pliocene-Quaternary contourite depositional systems have a long common evolution that could be simplified into two main stages, with an initial- and growth-drift stages. The late Miocene system is buried with dominant hemipelagic late Messinian (~6.4 - 5.3 Ma) deposits but there is an absence of a buried-drift stage for the Pliocene-Quaternary system due to its ongoing nature of the contourite depositional system's evolution. These stages and their associated large-scale sedimentary architectures are common to drifts of various ages identified along other margins. Such a coincidence of features and architectures underlines the mechanistic evolution of drifts in response to the long-term behavior of water masses responsible for their formation. In the study case of the Gulf of Cadiz, the long-term development of these contourite depositional systems can be correlated with a coeval shallowing of sills, determining a change from an outflow to an overflow setting across the gateways through time. These long-term variations (>5-10 My) in paleo-circulation are driven by the evolution of oceanic gateways and tectonic events.

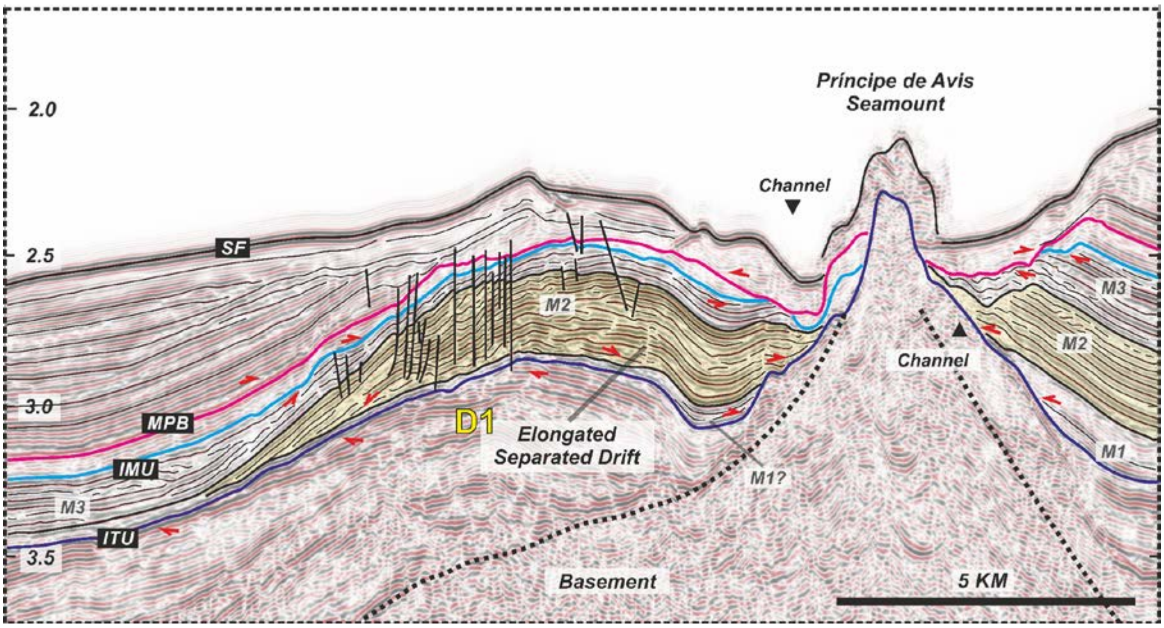

Figure 2. Seismic profile in the middle slope of southern West Iberian margin showing an example of an elongated separated drift (D1) associated with a contourite channel west of the Príncipe de Avis seamount. (For major sequences, subunits and main boundaries or discontinuities, see details in Ng et al., 2021).

Although the MOW circulation is quite homogeneous during the last decades, the internal sedimentary architecture of both the late Miocene and Pliocene-Quaternary contourite depositional systems indicated a complex stratigraphic stacking pattern of seismic units and subunits bounded by internal discontinuities and hiatuses in response to the intermittent behavior of the (paleo-) MOW at different temporal scales. These changes of approximately

0.4 and 0.8-0.9 My duration, overprinted by 2-2.5 My shifts, have been attributed to tectonic pulses. At shorter time scales (<0.4 Ma), climatic and eustatic changes driven by orbital cycles and oceanographic processes can cause deepening or shoaling/weakening, or enhancing of water masses and bottom currents through time. On top of that, the circulation of the MOW and other adjacent water masses (Eastern North Atlantic Central Water, ENACW; Antarctic Intermediate Water, AAIW; and North Atlantic Deep Water, NADW) have been very much affected by secondary oceanographic processes (tides, internal waves, eddies, etc.) which interact at different temporal and spatial scales, amplified by the adjacent gateways, which determined the local morphology and dominant sedimentary processes. The interaction of these processes is obvious at present day, but their influence in the preservation of the sedimentary record needs better understanding. These complex variabilities at the long- and short-term scales in turn influence the vertical distribution of sand and mud deposits as documented in the acoustic facies, sedimentary stacking patterns and thicknesses of contourite features at the exit of oceanic gateways.

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This project was funded by the Joint Industry Project supported by TOTAL, BP, ENI, ExxonMobil, Wintershall Dea and TGS within the framework of "The Drifters Research Group" at Royal Holloway, University of London (RHUL) and related to the projects CTM 2012-39599-C03, CGL2015-66835-P, and *CTM2016-75129-C3 (INPULSE Project).*

Contourite channels and gateways: the study case of the late Miocene South Riffian Corridor, Morocco

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Oceanic gateways are usually geological settings with high energy conditions where erosional features are predominant. Nevertheless, at the exit of the Gateways, or down current of the sill within gateways, started a complex combination of erosional and (sandy) depositional features that is not well known. Facies related to the erosional elements (i.e., contourite channels) of contourite depositional systems have not yet been properly established and related deposits in outcrop appear non-existent. On this contribution, the study case of the late Miocene South Rifian Corridor (Morocco) is presented, where a contourite depositional system has been defined (Fig. 1). The facies model and channel evolution are interpreted, and the bottom current overflow behaviour decoded (de Weger et al., 2020, 2021, 2022).

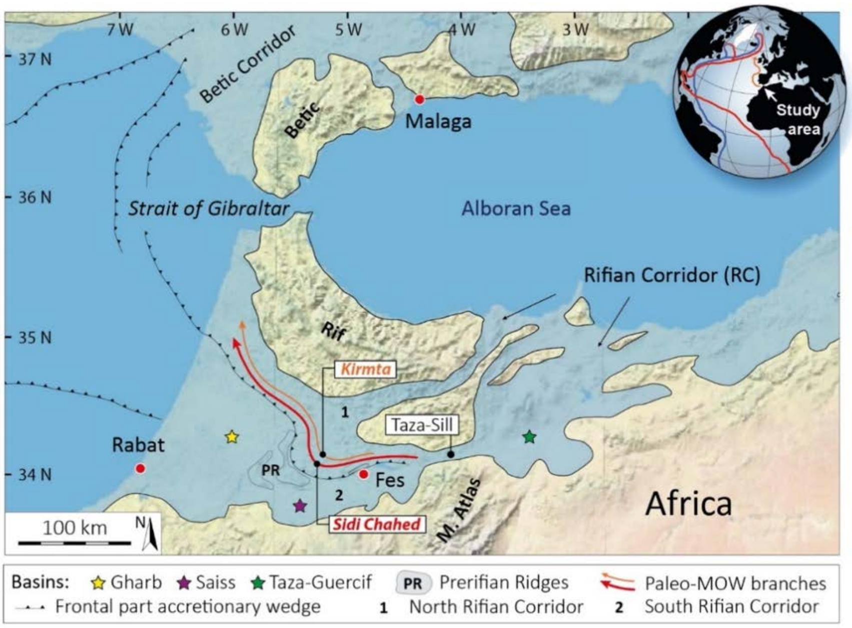

Figure 1. Paleogeographic reconstruction of the late Miocene Rifian Corridor, Morocco (de Weger et al., 2022). The Betic and Rif, Middle Atlas, Prerif Ridges, and the Taza-Sill form the main geological features. The studied outcrops are related to different branches of the paleo-Mediterranean Outflow Water (MOW). The small globe depicts the location of the study area, the general ocean circulation pattern and in orange, the trajectory of the present-day MOW.

This late Miocene (7.51 to 7.35 Ma) contourite depositional system in the South Rifian Corridor includes a contourite channel system related to the paleo-Mediterranean Outflow Water (MOW). Sedimentary facies have been recognized based on lithology, grain-size, sedimentary and biogenic structures. These facies were subsequently grouped into five facies associations related to the main interpreted depositional processes (hemipelagic settling, contour currents and gravity flows). The vertical sedimentary facies succession records the tectonically induced, southward migration of the contourite depositional systems and the intermittent behaviour of the paleo-MOW, which is mainly driven by precession and millennial-scale climate variations. Tides substantially modulated the paleo-MOW on a sub-annual scale.

Two contourite channel branches were identified (Fig. 1) consisting of three vertically stacked channelized sandstone units encased in muddy deposits (Fig. 2). Both branches have different channel-fill characteristics. It was found that the contourite channel evolution and facies distribution are related to spatiotemporal changes in flow characteristics of the paleo-MOW. The recognized channel facies distribution correlates well with previously established bedform stability diagrams. Erosion and upper-stage flow regime bedforms are associated with the most vigorous bottom currents, generally related to its core. Laterally, following the decrease in flow velocity towards the adjacent drift, bedforms comprise dunes, lower-stage plane bedforms and more heterolithic facies. Similar facies changes are also observed down-channel, related to a decrease in flow velocities resulting from turbulent mixing of water masses, associated decreases in density gradients and the subsequent deceleration due to gravity. Results of this work have been used to propose a 3D facies model for channelized sandy contourites.

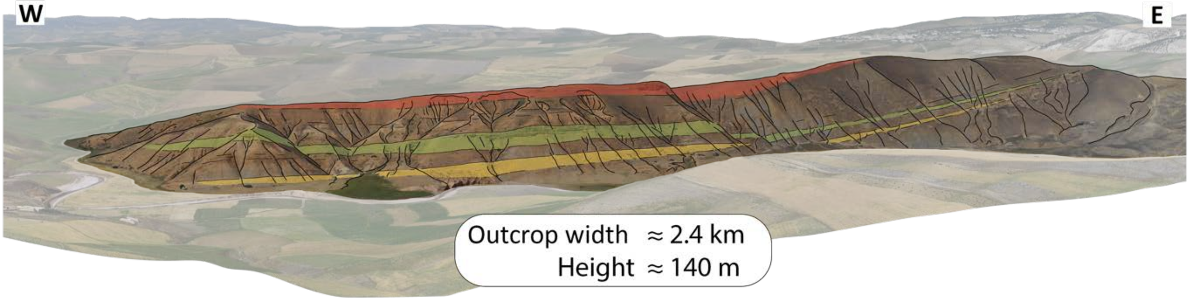

Figure 2. Panoramic picture of the of the Kirmta outcrop photographed towards the north. In yellow, green, and red respectively the paleochannels.

This work shows exceptional examples of muddy and sandy contourite deposits in outcrop by which a facies distribution model for the exit of a Gateway, the contourite channel to its adjacent contourite drift, is proposed. Our findings provide strong evidences for intermittent behaviour of overflow controlled by tectonic processes and regional climatic change. This model serves as a reference for contourite recognition both in modern environments and the ancient record with interesting implications for industry geoscience.

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This work was funded through the Joint Industry Project (JIP) supported by BP (United Kingdom), ENI (Italy), TOTAL (France), ExxonMobil (United States), Wintershall Dea (Germany) and TGS (United Kingdom) within the framework of "The Drifters" Research Group at Royal Holloway University of London (RHUL).

Contourite (paleo)channels and gateways: evidences of the intermittent MOW circulation after the opening of the Gibraltar Strait

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The present-day Strait of Gibraltar is one of the important oceanic gateways worldwide, opened at the end of the Miocene. Offshore seismic reflection data analyses from the southern continental slope of the Gulf of Cadiz at the exit of the Strait of Gibraltar reveals a succession of deeply incised valleys/channels, channel fills, and mounded structures. This opens up new evidences of the onset and intermittent behaviour and evolution of the Mediterranean Outflow Water (MOW) circulation during the Pliocene and Quaternary after the opening of the Strait of Gibraltar. Nine different paleochannels (PC) were identified that developed simultaneously to regional unconformities related to nine major Seismic Units (SU) (Fig. 1). Their correlation to IODP Exp. 339 Sites and regional chronostratigraphy have enabled us to comprehend the sedimentary evolution of these channels. As a result, three tectono-sedimentary stages have been differentiated. Within the first tectono-sedimentary stage, (*latest Miocene to Early Quaternary*), five channels are recognized (PC-1 to 5 and SU 1 to 4) about 4 km eastward from the Present-day channel. All these channels are developed in a central depression between two structural highs. The second stage (*Early Quaternary to Late Pleistocene*) is characterised by the displacement of three channels (PC-5 to 9 and SU-5 to 8) as well as the formation of adjacent smooth mounded drifts on their distal side located at similar place than the Present-day channel location. The latest stage comprises the *Late Pleistocene to Present* (PC-9 to seafloor and SU-9). During this period the southern channel maintained its present-day location and morphosedimentary characteristics. High-amplitude reflections are observed in channel facies, whereas the intercalation of low-amplitude and high-amplitude reflections are seen laterally in contourite drifts. After PC-5, there is also an increasing reflectivity of contourite drift facies proximal to contourite channels.

The variable locations and depths of the channel incisions and channel infill suggest local variations in the erosive capacity of the MOW, conditioned mainly by the inherited regional basin topography and the presence of local topographic highs. De Weger *et al.* (2020) reported the intermittent behaviour of the paleo-MOW during the Late Miocene and the present work confirms that behaviour during the Pliocene and the Quaternary, highlighting the complex interplay of tectonic changes and climatic variability in controlling that variability at different scale on gateways. These variations show a long-term intermittent behaviour of the MOW, which correlate with main tectonics events, of about 0.8–0.9 Ma duration with a pronounced overprint of ~2–2.5 Ma cycles, and shorter-term climatic (orbital) cycles of ≤0.4 Ma.

Contourite channels, filled by coarse (sandy) facies, have been recognized to contain large amounts of well-sorted sands associated with adjacent mud-prone contourite drifts, which can constitute effective storage/seal formations for antropogenic CO_2 and sustainable energies. The studied modern and buried channels are great analogues for ancient contourite channels that could potentially represent valuable reservoirs for underground geological storage exploration.

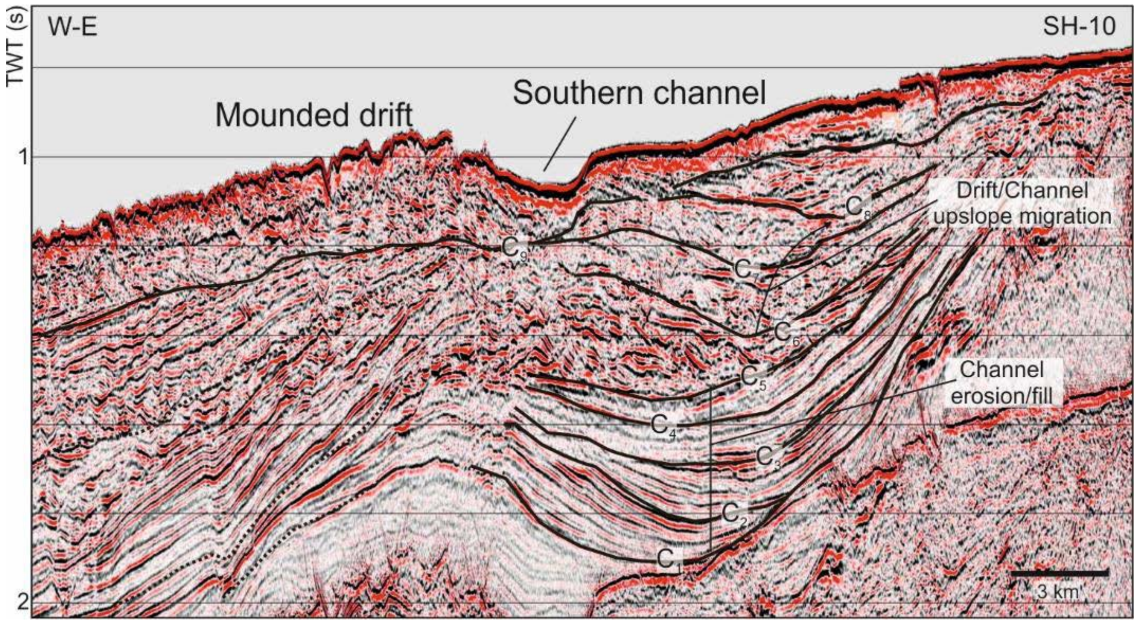

Figure 1. Multichannel seismic profile from the Gulf of Cadiz contourite depositional system showing the distribution of the erosive base of contourite channels developed coeval with regional discontinuities (from old to young; C1–C9) (de Weger *et al.,* 2022-in press, Sedimentology). Seismic line provided by REPSOL.

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De Weger, W., Hernández-Molina, F.J., Sierro, F.J., Chiarella, D., Llave, E., Rodriguez-Tovar, F.J., Miguez-Salas, O., Manar, M., 2022-in press. Contourite channels: facies model and channel evolution. *Sedimentology*.

The research was conducted in the framework of 'The Drifters Research Group' of the Royal Holloway University of London (UK), and it is related to the projects CTM 2012-39599-C03, CGL2016-80445-R and CTM2016-75129-C3-1-R. This research also used data collected through the Integrated Ocean Drilling Program (IODP). D. Duarte thanks the FCT (Fundação para a Ciência e a Tecnologia) - the Portuguese Science Foundation through the PhD grant SFRH/BD/115962/2016.

Contour current deposition in the South Orkney Microcontinent (southern Scotia Arc, Antarctica) and their link with the opening and evolution of the of the Drake Passage

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The final stages of the Gondwana break-up caused the separation of the former land bridge between South America and Antarctica and the subsequent opening of the deep oceanic gateway of the Drake Passage (*Dalziel et al., 2013*). The opening of the Drake Passage affected climate (i.e., modelled 1.5-2.5ºC cooling of the deep ocean), oceanographic structure and dynamics, including the formation of the Antarctic Circumpolar Current (*Toumoulin et al., 2020*). Despite its relevance for the global climate and ocean circulation, many uncertainties remain with an ongoing debate about the timing of the opening and deepening of the Drake Passage that relay on when and how the dispersion of the continental blocks occurred in the Scotia Arc.

In the southern Scotia Arc, the South Orkney Microcontinent (SOM) represents the largest continental block in the former connection between South America and the Antarctic Peninsula. The Bouguer and Eötvos basins are N-S trending sedimentary basins in the SOM (Fig. 1), which formation has been linked to the development of the Scotia Arc (*King and Barker, 1988*). Thus, the sedimentary record in these basins provides an opportunity to better understand the complex tectonic and palaeoceanographic evolution during the early stages of the Scotia Arc opening. We have identified distinct seismic units and their bounding unconformities in multichannel seismic reflection profiles (MCS) compiled from the Seismic Data Library System (SDLS). The age model of the seismic units has been accomplished through the correlation of the seismic reflection data with the Ocean Drilling Program (ODP) site 696. The site was drilled in the Eötvos Basin to a depth of 650 meters below seafloor (mbsf) and recovered sediments spanning from the late Eocene to the Quaternary.

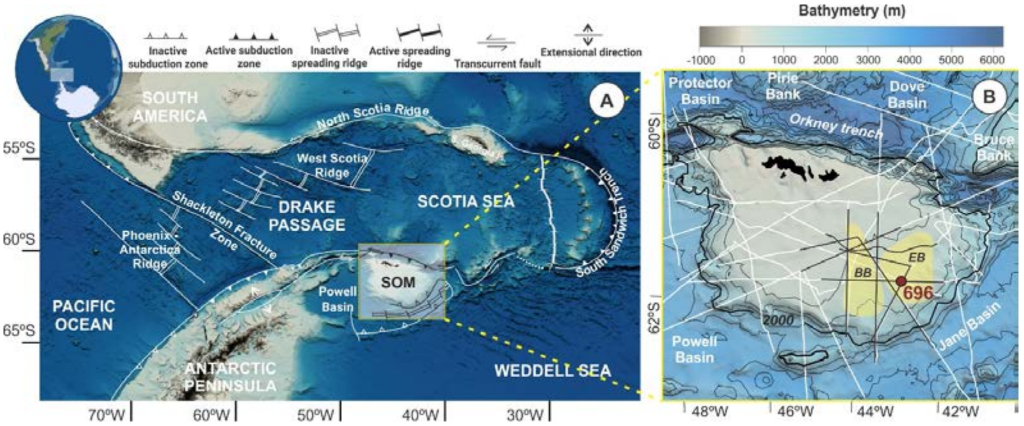

Figure 1: Geological setting of the study area. A) Tectonic setting of the South Orkney Microcontinent (SOM). B) Location of the multichannel seismic reflection profiles available at SDLS over the SOM (white lines) and the profiles used in this work (black lines). The location of the ODP 696 site and the Bouguer (BB) and Eötvos (EB) sedimentary basins (yellow shade, modified after Bussetti et al, 2001) are also shown.

Our results show a major erosional surface in the SOM during the Eocene-Oligocene transition (EOT). Above the EOT boundary, incipient development of contour current deposits over the southern part of the SOM is observed. This is followed by a phase of major development during the late Oligocene/early Miocene to the late Miocene. We map the distribution of contourite deposits and where possible, infer current directions to provide insights into past oceanographic reorganizations during early stages of the separation of the SOM from the Antarctic Peninsula after the opening and deepening of the Drake Passage.

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Alarm Bells are situated throughout the building and will ring continuously for an evacuation.

Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshall on that floor.

Fire Exits from the Geological Society Conference Rooms
Lower Library:
Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.

Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.

Main Piccadilly Entrance
Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid
All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

Facilities
The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of The Geological Society