The distribution of bounding surfaces in erg-marginal aeolian sediments: Implications for sub-surface fluid migration.

Keele University in collaboration with Oslo University, the British Geological Survey, the Utah Geological Survey and Wolverine Gas & Oil.

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Bounding surfaces in aeolian strata exist at a variety of scales and very strongly control fluid flow in the subsurface. Example from Zion National Park, Utah.

Aeolian strata act as some of the best hosts of geofluids in the subsurface. They have excellent potential as prospective targets for CO_2 storage, as well as forming significant aquifers, and productive hydrocarbon reservoirs. The ability of aeolian strata to transmit fluids depend upon the textural characteristics of the matrix along with the presence, geometry and inter-relationships of depositional surfaces (typically termed 'bounding surfaces') within the sediment. On the timescales over which fluids migrate naturally within the subsurface, bounding surfaces play a part in transmitting fluids, but the porosity and permeability profiles of the sediment matrix itself predominantly control fluid migration and the sediment's ability to host significant fluid volumes. Because of the well-sorted, quartz-dominant nature of aeolian sediments, matrix porosity and permeability are reasonably predictable within the subsurface with the limited and sparse data provided by the well bore.

However, on human timescales, the bounding surfaces contribute significantly to fluid movement. They may act as baffles or conduits to flow that seriously affect the efficiency of fluid injection and extraction, as well as controlling volumes recovered or sequestered. They occur over a range of spatial scales and represent both localised depositional and preservational processes within the aeolian system, through to regionally extensive surfaces controlled by allocyclic processes.

On small spatial scales, bounding surfaces are controlled principally by dune and interdune migration. Their geometry, attitude, frequency and fluid transmissibility can be predicted away from the well bore with varying degrees of success. Such predictions rely heavily upon a working knowledge of the nature of the aeolian system that deposited the sediment, and reliable identification of surface types from down-hole data. To date, most research in this field has concentrated upon the preserved sediments of well-developed aeolian systems where transverse duneforms dominated (e.g. Mountney & Jagger 2004; Loope *et al.*, 2012) and the models that resulted from this work have proved useful for characterising subsurface settings of similar style (e.g. George & Berry, 1993; Mancini *et al.*, 1990). However, several workers (e.g. Priddy & Clarke, 2020; Petigrew et al., 2020; Scotti & Veiga, 2018; Fryberger *et al.*, 2017; Nielson & Kocurek, 1987; Kocurek & Nielson, 1986; Rubin & Hunter, 1985) have recognised ancient preserved aeolian sediments in which transport and deposition was not dominated by transverse dune-forms. Consequently, transverse-dune models are far less applicable, or arguably inapplicable, for interpreting and understanding the bounding surfaces in preserved strata of settings where, for example, linear dunes dominate, or for the preserved strata of erg-marginal settings where the supply of aeolian sediment was low.

On larger spatial scales, bounding surfaces are controlled by the evolution of a sequence- (or 'cyclo-') stratigraphical framework in which cycles of aeolian sediment that represent periods of increasing aridity or humidity are bound by regionally extensive surfaces, themselves allo-cyclically controlled by climate (and accommodation space). These regional surfaces provide a framework for correlation across the aeolian system within which smaller scale bounding surfaces can be characterised and compartmentalised. The cyclic nature of the sediment they bound suggests that the surfaces may be controlled by Milankovitch cyclicity. Most field-based studies in this subject have concentrated upon erg-centre settings where preservation is dominated by drying-upward cycles of predominantly dune sediment bound by regional-scale 'flooding' or 'deflationary' cyclo-stratigraphical surfaces. The models developed by those studies are not directly applicable to erg-marginal settings where wetting upward cycles may be preserved in addition to drying upward (e.g. Pettigrew *et al.*, 2020). Again, application of these ideas in the subsurface relies upon reliable identification of these surface types from down-hole data.

This project will address these issues of bounding surface identification and prediction by focusing upon aeolian sediments in erg-marginal settings that are *not* dominated by transverse duneforms, and for which the over-arching cyclo-stratigraphical framework is not one of purely drying-upward cycles. The project will use a multidisciplinary approach of sedimentological outcrop study, geophsyical analysis and numerical forward modelling of sediment transport, deposition and preservation, to build generic models that predict geometry, attitude and frequency of different bounding surfaces. Fieldwork will concentrate upon the excellently exposed Jurassic erg-marginal strata of the Henry Mountains Basin in Utah, for which the Utah Geological Survey have recently completed a new lithostratigrpahical re-correlation (Doelling *et al.,* 2013; Sprinkel *et al.,* 2011). These strata represent deposition from a well-developed aeolian system on a marine margin within an overall transgressive regime. Studies of the Henry Mountains Basin will be augmented by further examples from the Jurassic strata of the Paradox Basin, Utah & Colorado.

Drone-based and terrestrial photogrammetric data collection methods will be used to acquire large, three-dimensional datasets from outcrop. Litho-facies analysis combined with 3D data visualisation and analysis techniques – advanced by the Basin Dynamics Research Group at Keele (e.g. Priddy *et al*., 2019; Priddy & Clarke, 2020) and by the British Geological Survey (Ellen *et al.,* 2019) – will be used to interpret fieldwork data to provide spatially constrained, 3D, geometric interpretations of units of different facies types and the surfaces that bound them.

From interpretations of field data, generic models of bounding surface geometry and distribution will be developed. Numerical forward modelling techniques will be used to develop numerical models of sediment transport, deposition and preservation that provide a means of predicting small- (dune-) scale surfaces. Cyclo-stratigraphical analysis of logged aeolian sections and correlation with the coeval marine sequence-stratigraphical framework will provide a means of examining larger scale bounding surfaces.

Most importantly, the work will include significant geophysical logging of outcrop examples to develop generic spectral gamma profiles that can be used to identify cycles of sediment and their bounding surfaces. These data will be compared with well-bore data through the same succession provided by Wolverine Gas and Oil. Preliminary work by the present authors has demonstrated that key bounding surfaces at all scales can be identified from the trends and breaks in the geophysical signature of spectral gamma. This approach provides a means of linking outcrop data to that from the subsurface in order to test developed models, but it also facilitates development of a generic set of 'electrofacies' for the identification of sediment cycles and bounding surfaces in erg-marginal aeolian deposits. Furthermore, the geophysical data provide a means of interpreting broader scale sedimentary cyclicity in terms of Milankovitch control. Published methods of determining frequency spectra from spectral gamma data will be applied to this work to examine, test and refine these ideas.

Work Plan:

- **Year 1 (2020/21):** Extensive literature review of aeolian and relevant marine processes and products; extensive literature review of the Temple Cap Formation and associated stratigraphy of the Colorado Plateau; introduction to available subsurface datasets; initial examination and interpretation of subsurface material to provide guidance for fieldwork; initial fieldwork in identified key sites to examine the aeolian system; processing of fieldwork datasets to interpret and numerically quantify aeolian bounding surfaces; University progression and year 1 review, including presentations to sponsors.

- **Year 2 (2021/22):** Initial development of geometric bounding surface models from fieldwork; development of evolutionary ideas; principal fieldwork period, including examination of the marine system; spectral gamma profiling; development of wireline data and models for bounding surfaces and cyclicity; AAPG ACE 2021 presentation; Paper 1 - Evolutionary models for bounding surfaces in erg-marginal sediments; University progression and end year 2 review, including presentations to sponsors.

- **Year 3 (2022/23):** Development of sequence stratigraphical and cyclic models from geophsycial data; Development of generic geophysical profile signatures; minor fieldwork to resolve any remaining issues; AAPG ACE 2022 presentation;

- **Year 4 (2023/24):** Paper 2 – Aeolian cyclicity from geophysical logs; thesis production and completion; final presentation to sponsors.

The project provides many opportunities for the student to work closely with the collaborators and to work within the facilities of the Utah Geological Survey, the University of Oslo and the British Geological Survey for extended periods over the course of the project. Furthermore, the Basin Dynamics Research Group strongly encourages research students to undertake internships (where available) with their collaborators for up to six months over the course of their degree.

Funding

This project is offered for competitive scholarship funding through the CDT in 'Geoscience for the Energy Transition'. Funding covers UK/EU Home fees, student stipend to RCUK levels, and a 5k pa Research Travel and Subsistence Grant (RTSG) to support fieldwork, conference attendance and training.

<u>Start Date:</u> September 2020

Application

This position would suit an applicant with a 2:1 or higher first degree in geology, geoscience or a related discipline, and a keen interest in sedimentology and geophysics, and some numerical background. An enjoyment of fieldwork is important. Some existing experience or background in aeolian sedimentology is useful, but not essential.

For further information on this project please feel free to contact the lead supervisor Dr Stuart Clarke at Keele University by email (s.m.clarke@keele.ac.uk) or by phone (+44 1782 733171).

For further information on the Basin Dynamics Research Group please see: *keele.ac.uk/bdrg/*

For further information on studying at Keele please see: *keele.ac.uk/pgresearch/howtoapply/*

Formal applications for the PhD study at Keele are handled centrally through Keele University's central admissions system: *keele.ac.uk/researchsubjects/geologygeoscience/*

Further information on the collaborators and sponsors:

The project integrates well into existing research by the Basin Dynamics Research Group at Keele, including projects that examine: the geometry and distribution of aeolian sediments in erg settings (Cousins *et al*., 2019); the variations in aeolian styles at marine and lacustrine margins (Cross; Regis); interactions between aeolian systems and erg-marginal continental and marine environments (Cousins; Priddy and Clarke, 2019; Pettigrew *et al*., 2019; Pettigrew *et al.,* 2020); reservoir modelling in continental settings (Mitten *et al.,* 2020; Priddy); climatic cyclicity in continental sediments (Pettigrew *et al.,* 2020; Regis); and allo-controls upon the evolution of basin fill (Mitten; Howell *et al.,* 2019).

The recent stratigraphical work by the Utah Geological Survey (Doelling *et al.,* 2013; Sprinkel *et al.,* 2011; Sprinkle *et al.,* 2009) provides a timely framework as well as ongoing research that this project will build upon and integrate with. The Utah Geological Survey (UGS) has an extensive interest in the Lower and Middle Jurassic formations of Utah, especially the aeolian deposits, because these formations form some of the most iconic landscapes in Utah, are proven petroleum reservoirs (Chidsey & Sprinkel, 2016; Chidsey & Sprinkel, 2014; Chidsey *et al.,* 2007; 2011; Sprinkel, 1982; Sprinkel & Waanders, 1984), are known to be significant aquifers, and are recognised more recently as potential targets for storage for CO_2 sequestration (Sprinkel *et al.,* 2011b; Doelling *et al.,* 2013). The UGS supports this work on the Temple Cap Formation and other Middle Jurassic formation for reasons above. The UGS maintains a Core Research Centre that contains core and cuttings of the Temple Cap Formation and other Middle Jurassic formations. This facility and its resources will be made available to researchers for this project. Doug Sprinkel is currently an emeritus geologist at the Utah Geological Survey. He provides an extensive data set, experience, and knowledge of surface and subsurface sections of the Temple Cap Formation, and its regional distribution.

The Tectonostratigraphic Research Group at the University of Oslo are at the leading edge of CO_2-related research in Norway, as the University of Oslo is hosting part of the Norwegian Carbon Capture and Storage (NCCS) centre of excellence, together with Sintef (Sundal *et al.,* 2017, Skurtveit *et al.,* 2017).This proposed project dovetails neatly with ongoing work of the group (in collaboration with Basin Dynamics Research Group) which has examined a contrasting arid-marine margin (Zuchuat *et al*., 2019) to the Temple Cap Formation and so can provide a comparative example for the proposed project. The Tectonostratigraphic Research Group has extensive expertise in the basin evolution of the study area during the Jurassic Period (Zuchuat *et al.,* 2018; 2019; Skurtveit *et al.,* 2017) that it will share with the proposed study.

Wolverine Gas and Oil have commercial interests in this part of the Jurassic Stratigraphy of the Colorado Plateau (Chidsey *et al*., 2011; Chidsey *et al.,* 2007), and they bring a wealth of background geological knowledge and subsurface fluid flow expertise to the collaboration (Hartwick, 2010a;b). Their portfolio of subsurface data including well resistivity image logs and geophysical subsurface data will be made available to constrain models developed by the proposed project.

The British Geological Survey has a global reputation for expertise in geoscience disciplines essential to the understanding and characterising the subsurface for multiple uses, including carbon capture and storage. The British Geological Survey will grant access to facilities and regional datasets that may be relevant for this project, but also contribute considerable expertise based on providing objective and rigorous scientific assessments of basin systems, and utilising these assessments to support government, industry and academia. Considering that the British Geological Survey has recently launched a new strategy, with significant emphasis on decarbonisation and the Energy Transition, this project would provide an ideal synergy between Keele University and the British Geological Survey.

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Cousins, D. Controls upon facies distribution and cyclicity in aeolian systems: Implications for successful exploration and development in a mature North Sea basin.

Cross, S. The development of aeolian-marine margins: The Moab Member of the Entrada Formation, Utah, USA

Regis, A. The development of lake margins, their interactions with contemporaneous continental environments and the implications for their reservoir potential.

Priddy, C. Climatic cyclicity and environmental interactions in arid continental basins: The Leman Sandstone, Southern North Sea.