Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
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Research Programme
- Short Call 2022 –
- Final Report -

Lead Applicant Name	Patrick A. Meere
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Host Organisation name	University College Cork
Project Title	A structural comparison of the southern Irish Variscan with the South Portuguese Zone.
Contract Number	2022-sc-007

This report covers the period 1st December 2021 to project end date (31/12/23)

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Final project report

Executive summary

Determining the sequencing of different deformation mechanisms and styles is crucial to understanding how the Earth's crust responds to tectonic stress. The sequence of near surface compressional deformation in peripheral orogenic forelands typically starts with an early stage of bulk homogenous shortening, i.e. layer parallel shortening (LPS) followed by folding and contractional faulting. The temporal and spatial distribution of strain is also very much influenced by the inherited basement structure and pre-collisional basin architecture in such foreland settings, in particular inherited extensional fault systems. Tectonic contraction in such settings tends to promote the positive inversion of basins through LPS, folding and reverse faulting by the exploitation of pre-existing bounding structures and facilitated by the lower bulk density and strength of sedimentary fill sequences when compared to the surrounding basement. This study combines conventional structural field studies from the Variscides of SW Ireland and southern Portugal with the spatial characterisation of finite strain using clast shape analysis and anisotropy of magnetic susceptibility (AMS) studies on deformed sandstones as a means of elucidating the temporal and spatial evolution of deformation in an orogenic foreland that is heavily influenced by pre-existing basement architecture and structures. AMS is increasingly seen to be a particularly sensitive proxy for tectonic strain signals in low to medium strain settings on the periphery of orogens. The Variscan of SW Ireland and Portugal offers an excellent opportunity to investigate the full foreland strain cycle from early bedding parallel oblate fabrics to more prolate intermediate fabrics and finally cleavage parallel oblate fabrics in an overall setting that incorporates marked basement control of the spatial distribution of finite strain. The adopted multi-technique approach also allows for insights into the relative timing of deformation events.

Introduction

Determining the sequencing of different deformation mechanisms and styles is crucial to understanding how the Earth's crust responds to tectonic stress. The sequence of near surface compressional deformation in peripheral orogenic forelands typically starts with an early stage of bulk homogenous shortening, i.e., layer parallel shortening (LPS) followed by folding and contractional faulting. The temporal and spatial distribution of strain is also very much influenced by the inherited basement structure and pre-collisional basin architecture in such foreland settings, inherited extensional fault systems. Tectonic contraction in such settings tends to promote the positive inversion of basins through LPS, folding and reverse faulting by the exploitation of pre-existing bounding structures and facilitated by the lower bulk density and strength of sedimentary fill sequences when compared to the surrounding basement. This study combines conventional structural field studies with the spatial characterisation of finite strain using clast shape analysis and anisotropy of magnetic susceptibility (AMS) studies on deformed sandstones as a means of elucidating the temporal and spatial evolution of deformation in an orogenic foreland that is heavily influenced by pre-existing basement architecture and structures. AMS is increasingly seen to be a particularly sensitive proxy for tectonic strain signals in low to medium strain settings on the periphery of orogens. The magnitude and orientation of the maximum (K_1), intermediate (K_2) and minimum (K_3) magnetic susceptibility axes of the AMS ellipsoid tend to correspond to the three principal axes of the finite strain ($X \geq Y \geq Z$). Early depositional fabrics are typically reflected by a very oblate AMS ellipsoid with K_1/K_2 usually indistinguishable and parallel to bedding. With the onset of tectonic deformation, the K_2 axis is progressively shortened in the direction of s_1 with K_1 defining a strong lineation perpendicular to the shortening direction which if fully developed produces a prolate AMS ellipsoid geometry. Ongoing tectonic shortening and flattening will push the AMS ellipsoid back into the oblate field with the K_3 axis now parallel to tectonic shortening. The Variscides of SW Ireland and southern Portugal offer an excellent opportunity to investigate this full foreland strain cycle in a setting that incorporates marked basement control of the spatial distribution of finite strain. The adopted multi-technique approach will also allow for insights into the relative timing of these events.

Structural Field Studies

Structural field studies were carried out across the Iveragh and Dingle peninsulas and Kerry Head focusing on Variscan tectonic cleavage development and folding. The purpose of this work was to characterise any changes in macroscopic structural styles and orientation across a significant basin margin fault, the Coomnacronia Fault. These data were categorised into three settings with respect to the Munster Basin margin (Coomnacronia Fault); Zone 1: the southern Intrabasinal Zone, Zone 2: the Basin Footwall Margin Zone and Zone 3: the northern Extrabasinal Zone. Structural fieldwork was also carried out along a complete N-S transect across the southern sector of Variscan South Portuguese Zone again to characterise structural styles and potential strain gradients across this tectono-sedimentary zone.

Zone 1 Intrabasinal Zone Munster Basin

Variscan deformation within the Munster Basin south of the northern basin margin Coomnacronia Fault is characterised by the development of significant LPS (over 45% tectonic shortening) followed by regional folding. (Cooper *et al* 1986, Meere 1995). This folding is developed at three scales form region kilometre scale anticlinoria/synclinoria to second order decametre folds and parasitic third order meter scale structures. Cleavage is generally best developed in the finer grained lithologies where it is highly penetrative. It is always steeply dipping and axial planar to folds, generally symmetrically fanning about axial planes. The implication is that the early LPS fabric was there was ongoing passively rotation of the fabric into the flattening (XY) plane during and possibly after folding.

Zone 2 Basin Footwall Margin Zone Munster Basin

Variscan deformation within this transitional zone is quite similar to that seen in Zone 1 with two important differences. Firstly, folding is not as intensively developed with more open asymmetric geometries that consistently verge to the north. Secondly, the well-developed cleavage related to early LPS consistently exhibits a pervasive, northerly directed, simple shear that occurred prior to folding. This fabric was subsequently passively folded resulting in a fabric that consistently dips to the south irrespective of its location on a given fold.

Zone 3 Extrabasinal Zone Munster Basin

Deformation in Zone 3 is characterised by symmetrical open folding and locally developed weak disjunctive cleavage that generally maintains a high angle to bedding indication indicating passive rotation of an early weal LPS fabric during folding.

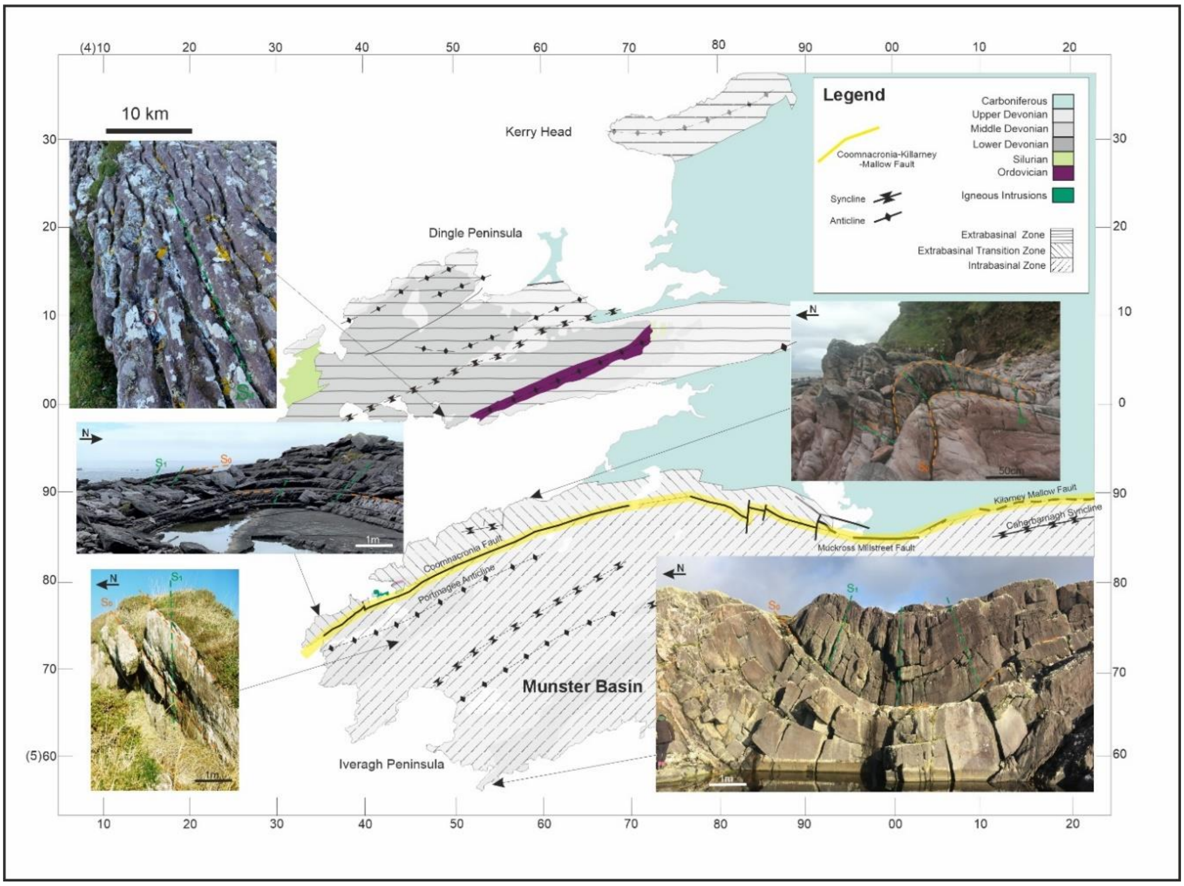


Figure 1 *Main structural styles across the northern margin of the Upper Devonian Munster Basin.*

South Portuguese Zone (SPZ)

Structural data were collected from eight localities along a transect across the southern extent of the SPZ known locally as the Southwest Portugal domain. The dominantly marine siliciclastic sequence exhibits the expected structures of a classic thin-skinned fold/thrust belt. While the folding is quite intense (tight to very tight in places) the associated tectonic cleavage is not well developed indicating limited internal penetrative strain was achieved by Variscan shortening.

Strain Analysis

Finite strain analysis was carried out on 33 medium/coarse grained Upper Devonian sandstones from the Iveragh and Dingle peninsulas and Kerry Head to again investigate the potential change in the Variscan strain regime across the Coomnacronia Fault (CF). Strain analysis has been carried out using the Delaunay Triangulation Nearest Neighbour Method (DTNNM) (Mulchrone, 2002) and the Mean Radial length MRL method (Mulchrone *et al*., 2003) using the software developed by Mulchrone *et al*. (2013) on Mathematica. Twenty of these samples are from the same samples as the AMS samples to allow a direct comparison of the strain data with the AMS data. Thin sections have been cut parallel to the bedding plane as this orientation is mostly likely to minimise the effects of sedimentary fabrics on tectonic finite strain estimates. The results (Figure 2) clearly demonstrated a northerly drop in the sandstone strain estimates on crossing the CF, i.e. the northern margin of the Munster Basin.

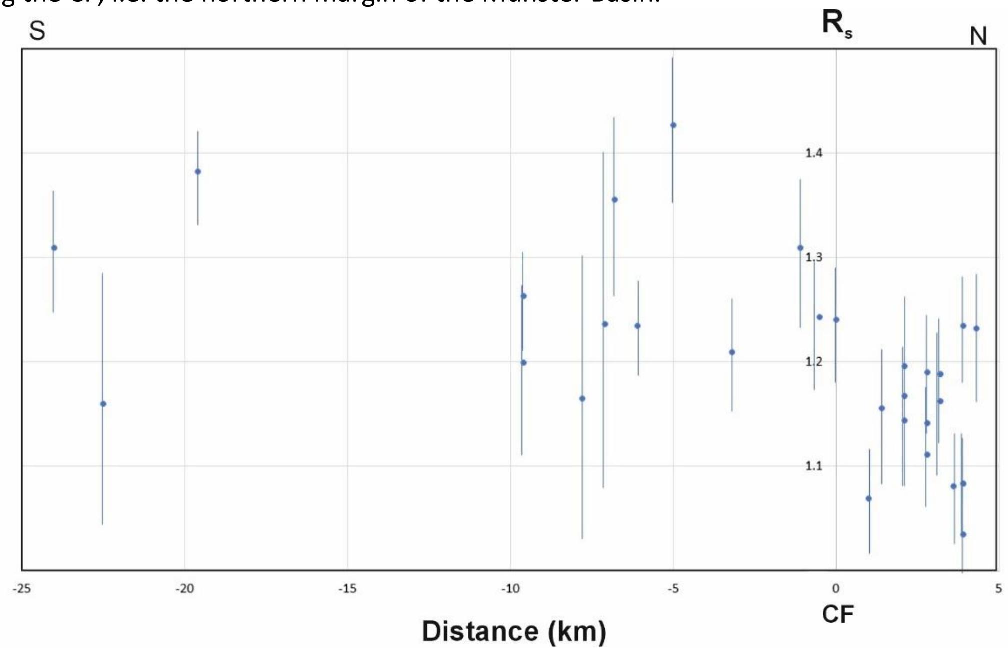


Figure 2 *Sandstone clast fabric strength (Rs) determined form the Mean Radial Length method (Mulchrone et al. 2003, 2013) from a section across the Munster Basin Margin (CF). Errors associated with the method are calculated from the bootstrap method.*

AMS Analysis

The anisotropy of magnetic susceptibility has been carried out on a total of 25 orientated sandstone block samples which were collected from selected locations on the Iveragh and Dingle peninsulas and Kerry Head and 8 oriented block samples from the SPZ. Samples of similar grain size and mineralogy were selected to maximize their comparability. The samples consist mostly of quartz/feldspar (80 - 90%), detrital micas and very fined grained matrix (< 15%) composed of micas, quartz and minor amounts of accessory minerals (i.e., oxides). AMS analysis was carried out using the AGICO KLY-3S Kappabridge. The Kappabridge operated at room temperature in a magnetic field of 300 A/m at a frequency of 875Hz. The AMS data was statistically analysed using Anisoft4.2 software (Chadima & Jelinek, 2009) to determine the mean susceptibility $k_m = (k_1 + k_2 + k_3)/3$, the magnetic lineation ($L = k_1/k_2$), the magnetic foliation ($F = k_2/k_3$). The degree of anisotropy ($P = k_1/k_3$) and the AMS ellipsoid shape ($T = 2\ln(k_2/k_3)/\ln(k_1/k_3)-1$) were calculated according to Jelínek (1981) and Tarling & Hrouda (1993).

Zone 1 Intrabasinal Zone Munster Basin

Zone 1 is characterised by predominantly prolate and tectonic oblate (K_3 axis orthogonal to tectonic fabric S_1) AMS ellipsoids (Figure 3). This is to be expected where the lithologies have experienced a significant amount of penetrative tectonic strain related to LPS. It has been estimated that LPS accommodated c. 48-50% crustal shortening prior to folding.

Zone 2 Basin Footwall Margin Zone Munster Basin

Zone 2 is a transitional zone characterised by predominantly tectonic oblate (K_3 axis orthogonal to bedding fabric S_0) and prolate AMS ellipsoids (Figure 3). This reflects an intermediate stage of the regional strain evolution with the in some case the original primary oblate ellipsoids being modified to prolate geometries by N-S tectonic shortening.

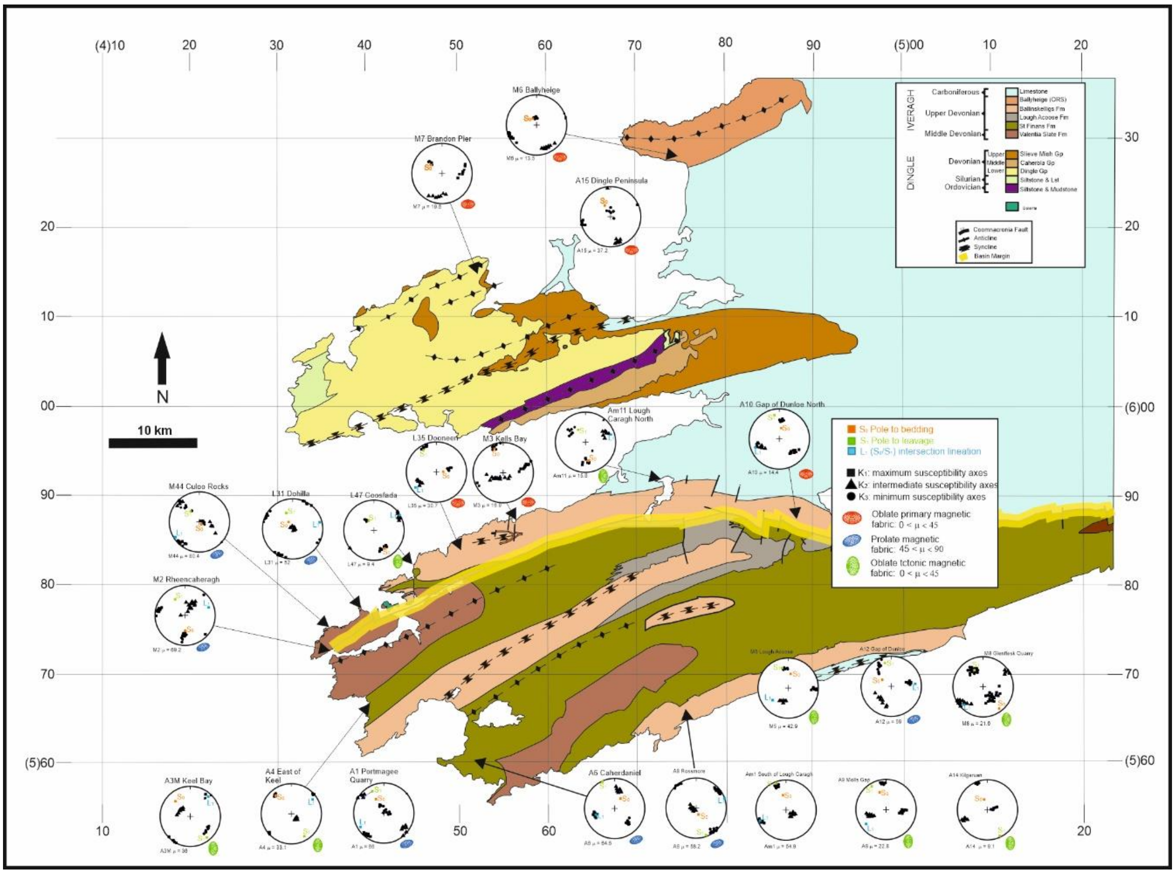


Figure 3 Stereographic projection plots of AMS principal axes demonstrating the predominance of K3) orthogonal to bedding in Zone 3 and orthogonal to cleavage in Zone 3.

Zone 3 Extrabasinal Zone Munster Basin

AMS ellipsoids for Zone are, as expected, characterised by sedimentary oblate geometries with little evidence of a tectonic overprint (Figure 3). This clearly reflects it's foreland position sitting outside the main area of Variscan penetrative tectonic deformation.

South Portuguese Zone (SPZ)

The eight calculated AMS ellipsoids for the SPZ consistently show oblate to weak prolate geometries with the K_3 axis generally at a high angle to bedding. This is somewhat similar to the transitional Zone 2 from the Irish Variscides.

Results, scientific/engineering targets reached beyond the state of the art and conclusions

A clear deformation sequence for the Variscan of SW Ireland consisting of early LPS cleavage development, followed by top to the north pervasive simple shearing of the sequence in the immediate footwall of the CF, followed by folding and late-stage reverse reactivation of the CF (Figure 4).

Basement architecture, especially at basin margins, fundamentally controls subsequent deformation patterns in foreland settings.

Footwall buttressing influences penetrative strain and tectonic fabric development and evolution in overlying cover sequences.

No oblivious variation in tectonic fabric development was evidenced from the calculated AMS ellipsoids from a N-S transect across the SPZ. The general alignment of the AMS K_3 axis at a high angle to bedding indicates the preservation of a sedimentary fabric that has not been significantly altered by tectonic shortening.

AMS proves to be a very useful tool in characterising strain regimes in peripheral orogenic lower-grade tectonic settings.

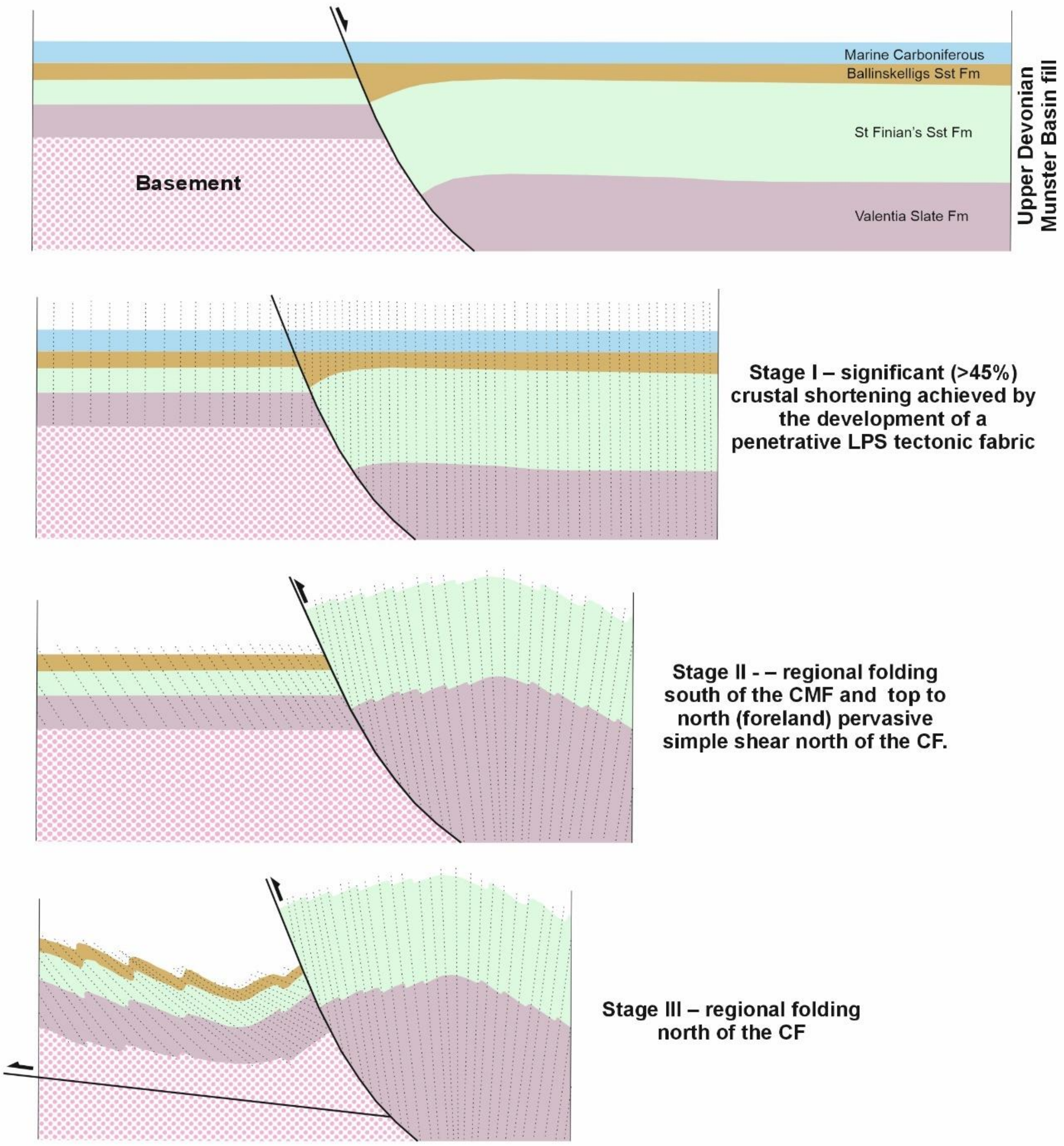


Figure 4 *The Variscan deformation sequence across the northern margin of the Upper Devonian Munster Basin.*

Project Implementation

Milestone No.	Milestone description	Delivery
1	Field data and AMS samples collected for both field areas.	Winter 2022
2	Deformation models for both field areas finalised.	Winter 2023

Task No.	Deliverable description	Delivery
1	Paper I submitted for publication (*Gondwana Research*): Basement controls on Variscan strain regimes during basin inversion form SW Ireland.	Spring 2024
2/3	Paper II submitted for publication (*Tectonophysics*): A characterisation and comparison of Variscan foreland deformation from SW Ireland and the South Portuguese Zone of southern Iberia including a new palaeographical interpretation of the western European Rhenohercynian Zone.	Not delivered.

Outputs to date
Oral research paper presented at EGU 2023, Vienna.
Research Poster presented at GSI Research Day 2023, Dublin.
Research Poster presented at Tectonic Studies Group Meeting 2024, University of St Andrews.
Research paper submitted to Gondwana Research (Spring 2024).

Impacts
Initial studies from which the results are expected to be used for Horizon Europe/EU applications – Reliable and unhindered access to raw materials is a growing concern within the EU and across the globe. We viewed this research project as a pilot study and consultation exercise for EU funding application.

Scientific discovery - The research has provided new and important insights into the role of basement architecture of basins situated in orogenic forelands on the spatial distribution of penetrative strain in these settings.

Improved subsurface resource assessment-The new understanding relating to the role of basement architecture on the distribution of finite strain in orogenic forelands will help inform exploration strategies for fault/vein hosted metal resource exploration. This is increasingly important in the drive for global decarbonization as critical raw materials will be essential for the deployment of low-carbon technologies.

Training & education programmes (not only project staff) – I have incorporated the outputs from this research into my advanced structural geology module (*GL3004 Applied Structural Geology*) delivered here in UCC.

Positive societal impact, economic development, and employment - The results from this research have will underscore a powerful educational and geo-tourism narrative. As a Co-PI for the LIVE project [https://www.ecomuseumlive.eu/] which was completed in the summer 2023, I will continue to tap into existing community links (including primary and second level schools) to promote the research outputs form this project as valuable educational and geo-tourism resources for southwest Ireland and beyond.

Communications and dissemination – I will be submitting a paper on our results to *Gondwana Research* in Spring 2024. I presented an oral paper on the research at the 2023 European Geophysical Union (EGU) conference in Vienna (see attached abstract). I presented a poster on the research at the annual 2023 GSI Research Day at Dublin Castle and the 2024 Tectonics Group Meeting at the University of St Andrews.

Task No.	**Deliverable description**	***Planned delivery (as per proposal)**	***Date of delivery**
1	Paper 1	November 2023	April 2024
2/3	Paper 2/Maps	December 2023	Not Delivered
4	Conference presentations	December 2023	April 2023, November 2023, January 2024.

Publications
Meere, P.A., Parker, C. E. 2023 The role of basement architecture in the spatial and temporal development of tectonic deformation in an orogenic foreland – An example from the Variscides of SW Ireland. *https://doi.org/10.5194/egusphere-egu23-9481 EGU General Assembly 2023*.

Meere, P.A., Parker, C. E. 2024 The contribution of inherited extensional faults systems to the spatial and temporal development of penetrative tectonic fabrics in an orogenic foreland - An example from the Variscides of SW Ireland. *Tectonic Studies Group Meeting 2024, University of St Andrews.*

Meere, P.A., Parker, C. E. 2024 The contribution of inherited extensional faults systems to the spatial and temporal development of penetrative tectonic fabrics in an orogenic foreland - An example from the Variscides of SW Ireland. Gondwana Research (In prep).

Deviations from original project plan

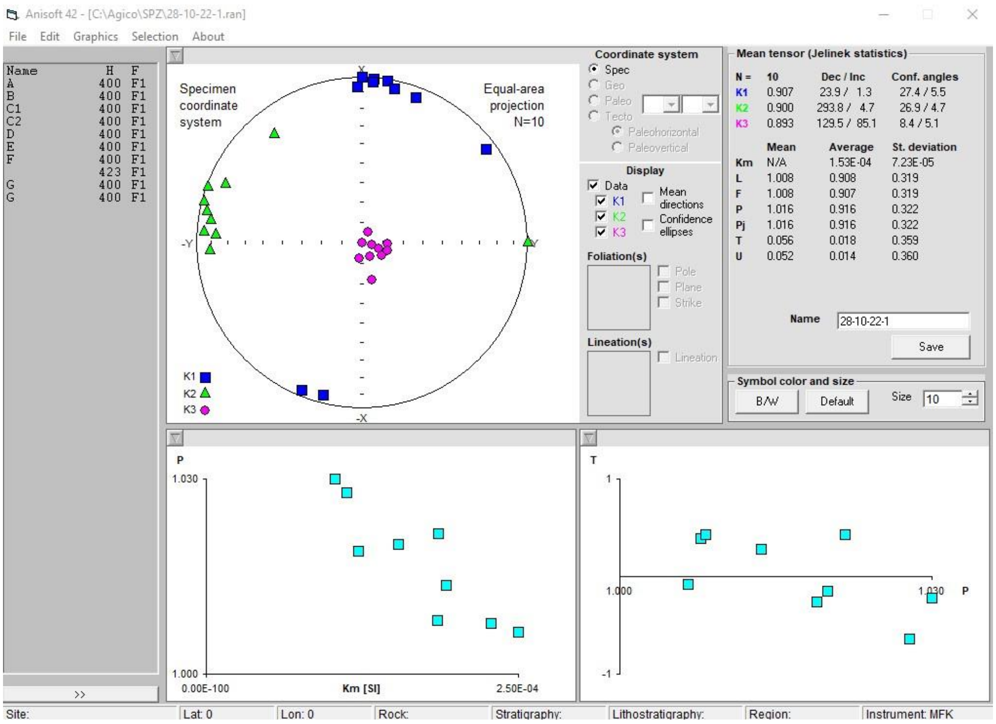
Description of deviation: The limited amount and quality of the data available from the SPZ, in addition to time/resource limitations has means that I am not in a position at this to produce a second paper from this project.

<u>Adaptation/Mitigation measures applied</u>: I will incorporate a comparison of the Irish and Portuguese foreland deformation regimes in *Gondwana Research* manuscript.
<u>Impact of deviation</u>: The project will now have one paper in a high-quality international journal (Gondwana Research - IF 8.2).

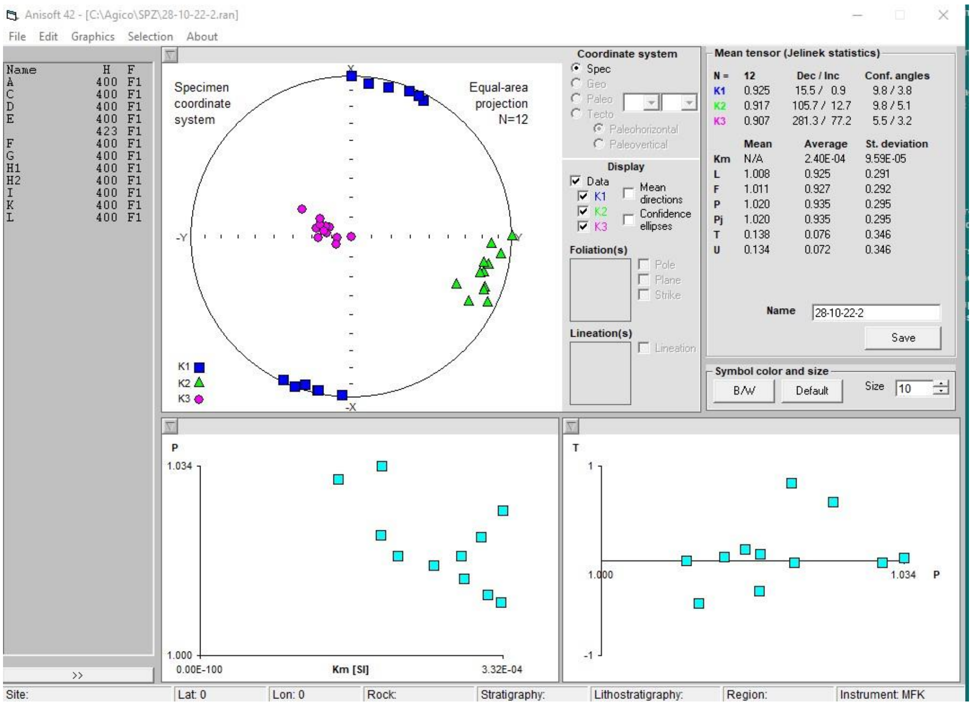
Have you contacted GSI staff in relation to your project? No.

3. ***Supplemental information/datasets*** *(please clearly mark any sensitive or confidential information that should not be published and include a justification for the request)*

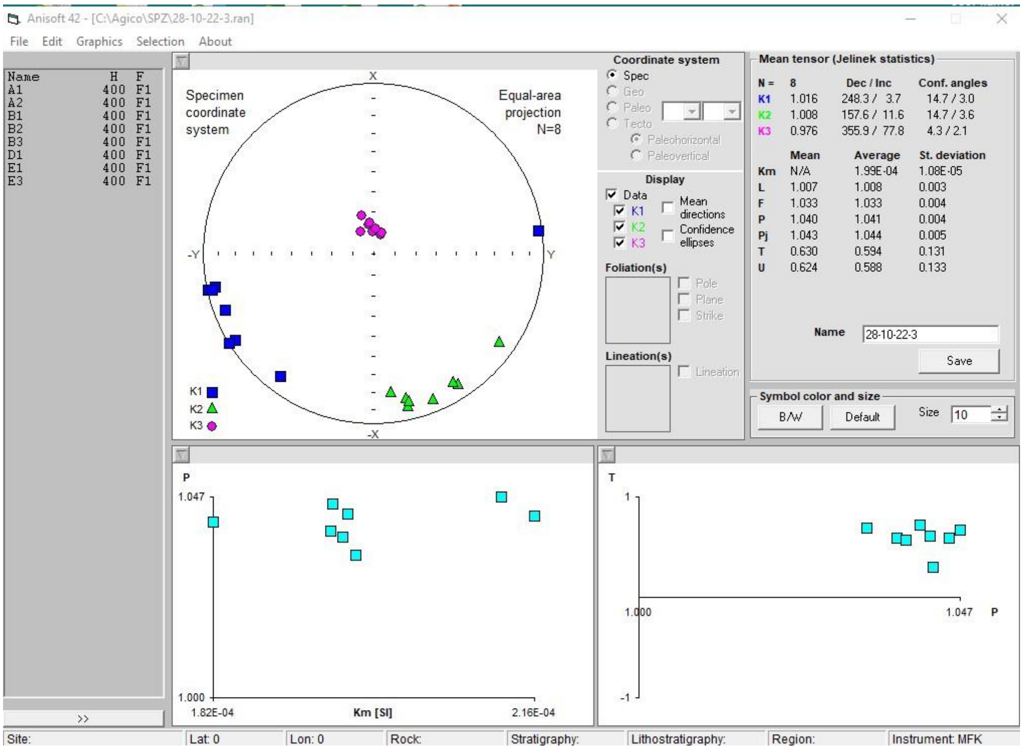
AMS Data for South Portuguese Zone Transect



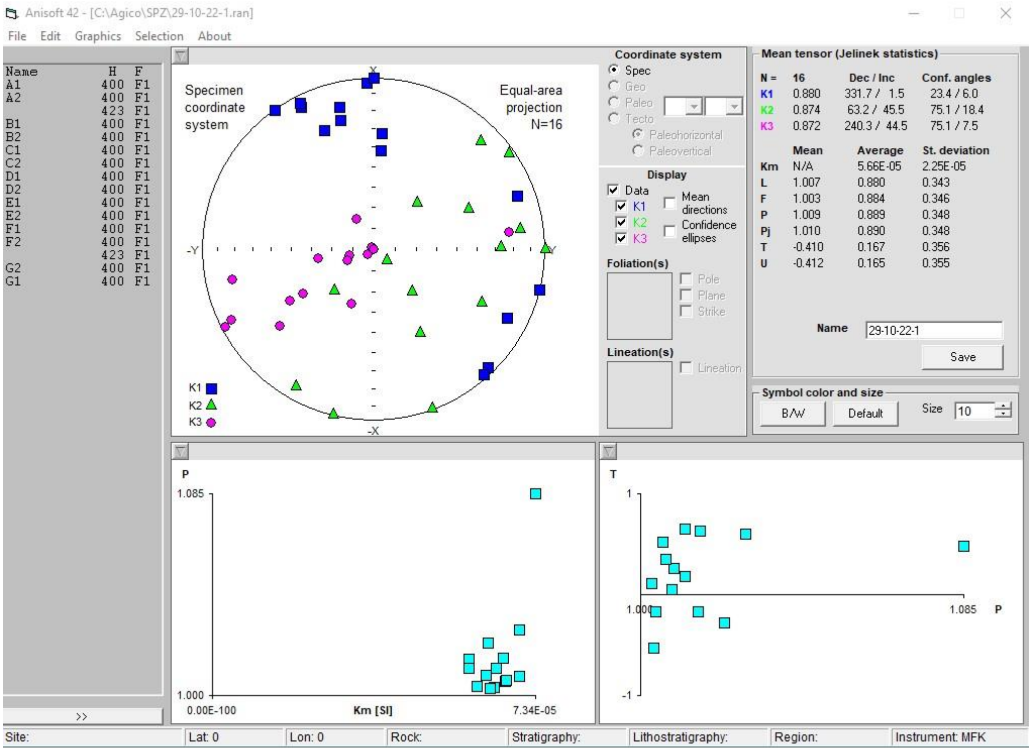
28-10-22-1 Almograve Beach



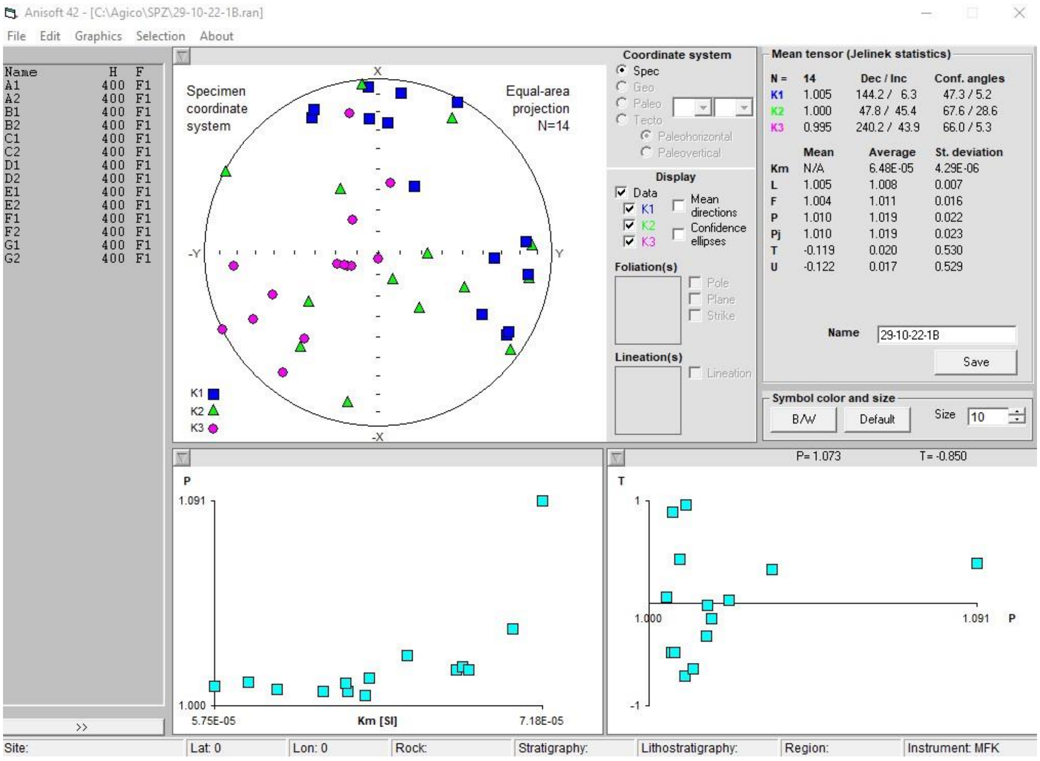
28-10-22-2 Almograve Beach



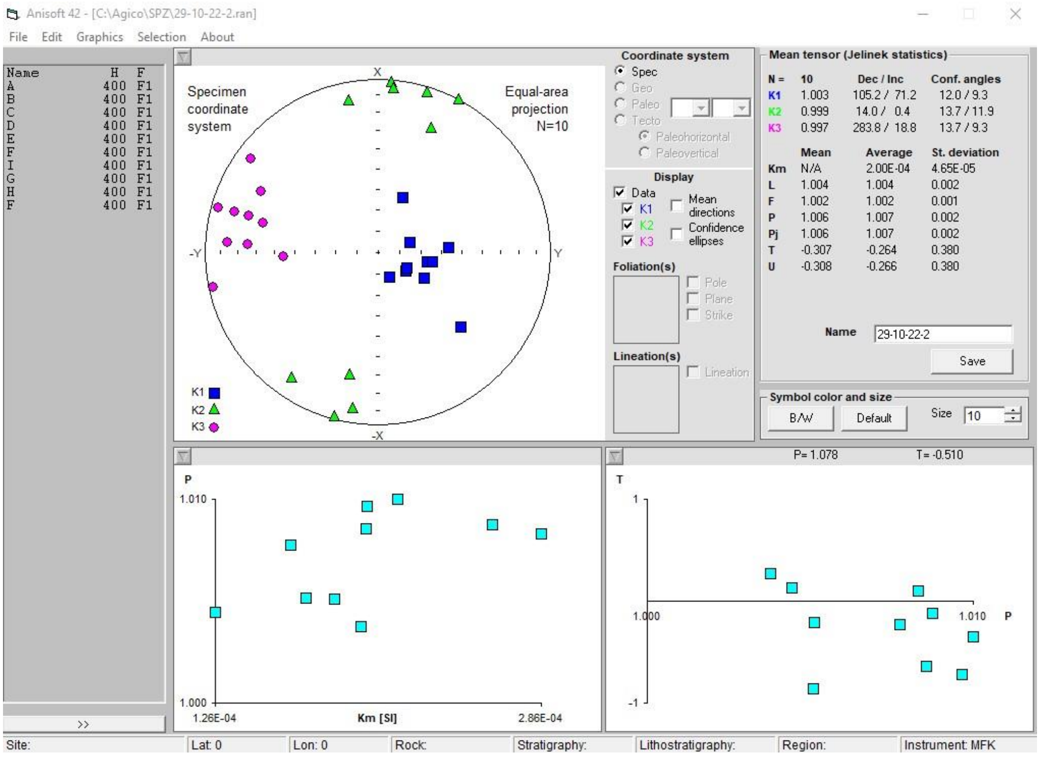
28-10-22-3 Arrifauna Beach



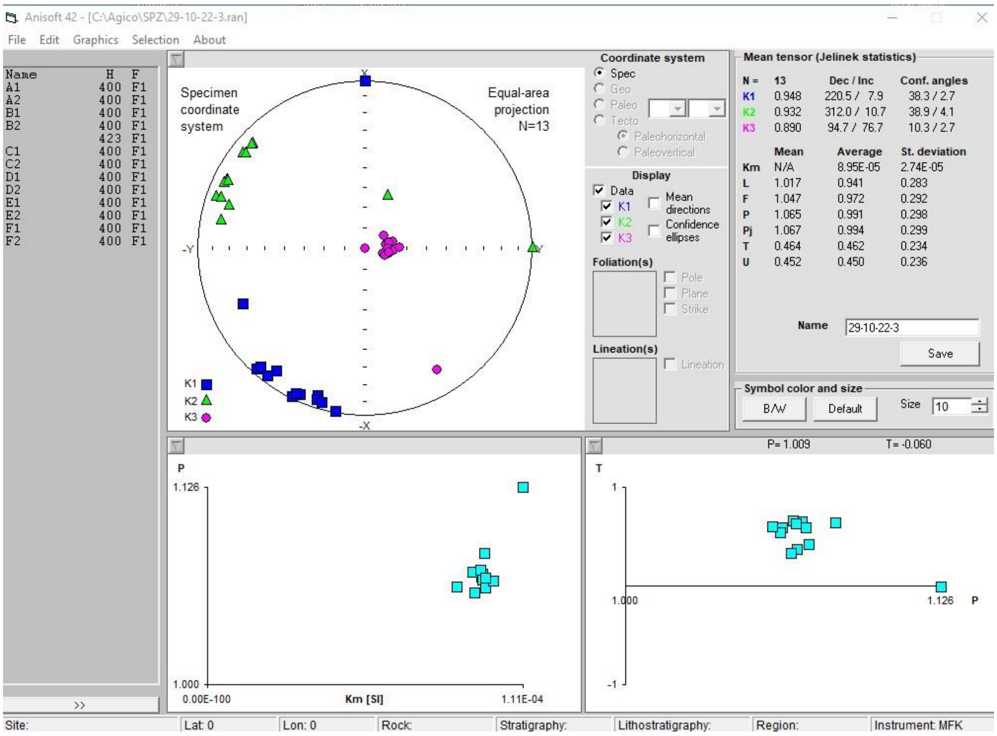
28-10-22-4 Zambujeira do Mar



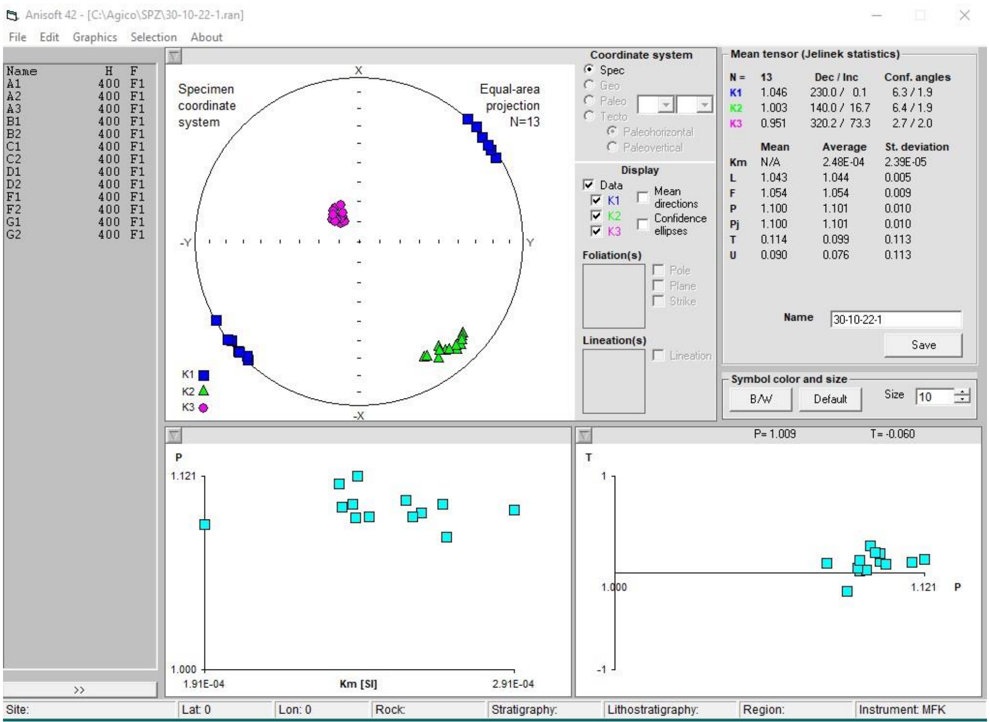
29-10-22-1 Cap Viacente



29-10-22-2 Marracao



29-10-22-3 Almograve



30-10-22-1 Porto Covo

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Appendix 1

EGU General Assembly
#EGU23
23 - 28 April 2023

EGU23-9481, updated on 30 Jan 2024
https://doi.org/10.5194/egusphere-egu23-9481 EGU General Assembly 2023

The role of basement architecture in the spatial and temporal development of tectonic deformation in an orogenic foreland – An example from the Variscides of SW Ireland.

Patrick A Meere[1] and Chloe R Parker[2]

[1]University College Cork, School of BEES, Geology, Cork, Ireland (p.meere@ucc.ie)
[2]Breedon GB Materials, Craigenlow, Craigenlow Quarry, Aberdeenshire, Scotland, AB32 7ED

Determining the sequencing of different deformation mechanisms and styles is crucial to understanding how the Earth's crust responds to tectonic stress. The sequence of near surface compressional deformation in peripheral orogenic forelands typically starts with an early stage of bulk homogenous shortening, i.e. layer parallel shortening (LPS) followed by folding and contractional faulting. The temporal and spatial distribution of strain is also very much influenced by the inherited basement structure and pre-collisional basin architecture in such foreland settings, in particular inherited extensional fault systems. Tectonic contraction in such settings tends to promote the positive inversion of basins through LPS, folding and reverse faulting by the exploitation of pre-existing bounding structures and facilitated by the lower bulk density and strength of sedimentary fill sequences when compared to the surrounding basement. This study will combine conventional structural field studies from the Variscides of SW Ireland with the spatial characterisation of finite strain using clast shape analysis and anisotropy of magnetic susceptibility (AMS) studies on deformed sandstones as a means of elucidating the temporal and spatial evolution of deformation in an orogenic foreland that is heavily influenced by pre-existing basement architecture and structures. AMS is increasingly seen to be a particularly sensitive proxy for tectonic strain signals in low to medium strain settings on the periphery of orogens. The Variscan of SW Ireland offers an excellent opportunity to investigate the full foreland strain cycle from early bedding parallel oblate fabrics to more prolate intermediate fabrics and finally cleavage parallel oblate fabrics in an overall setting that incorporates marked basement control of the spatial distribution of finite strain. The adopted multi-technique approach will also allow for insights into the relative timing of deformation events.

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Appendix 2

TSG
Tectonic Studies Group

January 2024

The contribution of inherited extensional faults systems to the spatial and temporal development of penetrative tectonic fabrics in an orogenic foreland - An example from the Variscides of SW Ireland.

Patrick A. Meere[1] & Chloe E. Parker[2]

[1] University College Cork, School of BEES, Geology, Cork, Ireland. (p.meere@ucc.ie)

[2] Breedon GB Materials, Craigenlow, Craigenlow Quarry, Aberdeenshire, Scotland, AB32 7ED.

The sequence of compressional deformation in peripheral orogenic forelands typically starts with an early stage of layer parallel shortening (LPS), followed by folding and contractional faulting. The temporal and spatial distribution of strain is also very much influenced by the inherited basement structure and pre-collisional basin architecture in such foreland settings, in particular inherited extensional fault systems. Previous studies have emphasised the role of these inherited extensional faults as 'buttressing' structures that restrict the foreland progression of thrusting and promote pure shear tectonic shortening.

In southern Ireland, the Variscan Rhenohercynian Zone is characterised by peri-Gondwanan basement with a Lower Palaeozoic cover sequence and overlying Devonian/Carboniferous basins that were deformed and inverted during Variscan compression. This study combines structural field studies with the spatial characterisation of finite strain using clast shape analysis and anisotropy of magnetic susceptibility (AMS) studies on deformed sandstones as a means of elucidating the temporal and spatial evolution of deformation in an orogenic foreland that is heavily influenced by pre-existing basement architecture. Basement architecture, especially at basin margins, fundamentally controls subsequent deformation patterns in foreland settings. Footwall buttressing influences penetrative strain and tectonic fabric development and evolution in overlying cover sequences. AMS proves to be a very useful tool in characterising strain regimes in peripheral orogenic lower-grade tectonic settings.