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Geomechanics and geology: introduction

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Geomechanics investigates the origin, magnitude and deformational consequences of stresses in the crust. Perhaps the earliest description of geology and mechanics was from the sandbox experiments of Willis (1891), and many of the guiding principles were developed by Anderson (1951), Hubbert & Willis (1957), Jaeger & Cook (1979) and Engelder (1992), with input from engineering disciplines (e.g. Griffith 1921). Subsequently, geomechanics has grown such that it now constitutes an important subdiscipline within the geosciences, as witnessed by the increase in SPE papers with 'geomechanics' in their titles (**Addis 2017**). In recent years, awareness of geomechanical processes has been heightened by societal debates on fracking, human-induced seismicity, natural geohazards and safety issues with respect to petroleum exploration drilling, carbon sequestration and radioactive waste disposal.

This volume includes a selection of the papers presented at the October 2015 meeting 'Geomechanics and Geology' held at the Geological Society, sponsored by the Petroleum Group and Tectonic Studies Group. The meeting was convened to explore the common ground linking geomechanics with *inter alia* economic and petroleum geology, structural geology, petrophysics, seismology, geotechnics, reservoir engineering, and production technology. A rich diversity of case studies showcased applications of geomechanics to hydrocarbon exploration and field development, natural and artificial geohazards, reservoir stimulation, contemporary tectonics, and subsurface fluid flow. This introduction selects some of the highlights from the meeting and identifies common themes from papers contained in the present volume and/or presented at the meeting.

What do we understand by geostresses? Couples (2015) observed that concepts of stress are essentially a normalization of forces that work well in homogeneous bodies. But rocks are fundamentally heterogeneous, and stress transmission within them often does not conform to continuum mechanics. A good analogy is photoelastic analysis of beads that show how stress is transmitted in granular materials through load-bearing 'force chains' surrounded by relatively unloaded zones. Couples (2015) suggests crustal stresses are best thought of, alternatively, in terms of elastic energy within rocks.

Stress azimuth can vary from uniformity over very large areas to pronounced swings over distances of a few metres. Inherent heterogeneity of large-scale geosystems is demonstrated by the degree of variation of stress azimuths shown by the *World Stress Map* (Heidbach *et al.* 2016), a compilation of maximum horizontal stress measurements from >6000 wells in >100 basins worldwide (Tingay 2015) and an excellent example of industry–academic collaboration. Tingay concludes that stress measured at any one point is the net result of all forces combining to act on it, from the plate-scale to the local-scale. Main processes controlling horizontal stress are:

- 'far-field' plate tectonic forces generated at forearcs, retroarcs, rifts, ocean ridges, passive margins, cratons, etc.;
- intraplate stress sources: for example, plumes;
- different types of sedimentary basin: for example, compare horizontal stress azimuth in rifts and foredeeps;
- isostasy and topographical body forces, particularly regions of only partially compensated positive and negative 'dynamic topography';

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- deglaciation;
- detachment zones: for example, isolation from far-field stresses of supra-detachment sequences in modern deltas;
- geological structures on various scales: for example, stress refraction around major faults and bending stresses within folds;
- mechanical stratigraphy: for example, vertical changes in stress gradient due to changes in elastic properties and focusing of higher magnitude stresses in lenses of stronger rocks within ductile shear zones

Tassone *et al.* (2017) provide an example from SE Australia of contradictory evidence for the state of contemporary stress from 'local' measured stress v. that inferred from plate boundary forces and Recent structures. Neotectonic deformation is dominated by thrust faulting and related folding, consistent with New Zealand plate collision, whilst leak-off tests from the Otway and Gippsland basins indicate strike-slip or normal faulting regimes. They attribute the difference to: (i) depth-controlled differences in mechanical stratigraphy; (ii) compartmentalization of stress according to whether neotectonic stress is accommodated by folding or faulting; and (iii) underestimating horizontal stress magnitude due to assuming that leak-off pressures are accommodated only by tensile failure.

Friction and faulting is investigated by **Fetter *et al.* (2017)** and **Richardson & Seedorff (2017)**. **Fetter *et al.* (2017)** describe Recent large-displacement, low-angle normal faults that offset the seafloor in the highly stretched and thinned crust of the Santos Basin, offshore Rio de Janeiro to investigate the influence of detachment zones on stress orientation. Underlying salt-cored listric faults are shown to have caused local rotation of the stress field such that none of the principal stresses are vertical. The Andersonian model that predicts fault type (i.e. steep normal faults, low-angle thrusts, vertical strike-slip) therefore no longer applies, allowing markedly 'non-Andersonian' fault angles to develop. They compare these structures with similarly active low-angle faults in California and Nevada, USA.

A good example of how mechanical stratigraphy controls stress patterns is provided by *in situ* stress measurements from the coal-bearing Bowen Basin, Queensland, Australia (**Tavener *et al.* 2017**). Regional stress is controlled by interplays between far-field plate boundary processes and more local basin-controlling structures. But at reservoir-scale, the stress state is highly variable laterally and vertically, changing from shallow (<600 m) thrust regime to deeper strike-slip. They attribute this stress complexity to the mechanical stratigraphy, particularly the low Young's modulus and Poisson's ratio of coals relative to their encasing clastics, meaning that coals are most highly stressed in the shallower thrust regime and vice versa at depth in the strike-slip regime. This observation is a powerful tool for predicting how reservoir sequences respond to fracture stimulation – the coals being easier to stimulate in strike-slip settings with fractures better confined to the coals, and vice versa.

Mechanical stratigraphy and the processes controlling it was the subject of a novel study of lava flows by Bubeck (2015). She observed from CT scans that vesicles in lavas become increasingly ellipsoidal towards the bases of the flows, their long axes orientated horizontally. This is attributed to progressive distortion of the vesicles with burial and loading. In the same way as the 'pointy' ends of an egg have relatively higher compressive strength, the lower parts of lava flows containing the most ellipsoidal vesicles are weak under vertical loading but much stronger in horizontal compression. This recognition of significant mechanical stratigraphy within lava flows has important implications for understanding volcano stability.

Several contributions showed how the influence of rock fabric on geomechancial behaviour can lead to phenomena that appear to deviate from well-established norms. Hackston (2015) compared frictional behaviour of mechanically contrasting sandstones using triaxial experimental apparatus. They found that: (i) failure angle in compression was always smaller than in extension, suggesting either stress refraction and/or the influence of microfractures (so-called Griffith cracks); and (ii) deviation of failure angle from classical Mohr–Coulomb theory, suggesting the active role of the intermediate stress σ_2. **Descamps *et al.* (2017)** examined the control that texture and diagenesis exert on geomechanical properties in chalk. They show that clay in argillaceous chalks increases rock strength because it promotes greater compaction and earlier diagenesis.

It is noteworthy that of the 30 papers presented at the meeting, 17 dealt substantially with the role of geofluids in facilitating rock deformation. Like stress, geofluids are a phenomenon that cannot usually be observed in action directly, but it is clear that understanding the impact they have on geomechanical processes is fundamental. We assert that almost no macro-scale brittle deformation in the upper crust takes place in the absence of elevated pore pressures because deviatoric stresses are not high enough to overcome frictional sliding resistance. Mechanisms that generate overpressure include compressional inversion (analogous to liberating porewater by wringing a sponge), exhumation (e.g. tensile failure linked to gas generation at peak burial: **English & Laubach 2017**; **English *et al.* 2017**), deglaciation (due to isothermal decompression), disequilibrium compaction (i.e. rapid burial leading to partial dewatering), metamorphic dehydration reactions and maturation of organic matter (especially volume expansion associated with conversion of kerogens to liquids and, with deeper burial, cracking of liquids to gases).

Several papers presented at the meeting examined relationships between pore pressures and deformation (**Gulmammadov *et al.* 2017**; **Lahann & Swarbrick 2017**; **Roberts *et al.* 2017**; **Sibson 2017**). For example, **Sibson (2017)** observes that megathrust earthquakes appear only to occur where pore pressure/lithostatic pressure ≥ 0.9 and infers that much of the seismogenic crust is critically stressed (i.e. on the verge of failure). This assertion is based mainly on the accumulation of evidence for fluid-driven failure from earthquakes generated by fluid injection down boreholes (e.g. Oklahoma: Keranen *et al.* 2013), and from reservoir-induced seismicity in various fields such as the Groningen gas field in The Netherlands (Grasso 1992).

Collettini (2015) investigated why earthquakes often nucleate in carbonates (e.g. Zagros, Italy, Oklahoma). Many limestones exhibit high permeabilities and it is therefore more difficult to maintain significant pore fluid overpressure. This is important because overpressures promote stable sliding, thus slowly dissipating elastic strains otherwise manifested by seismicity. Experiments reported by Collettini (2015) used a reshearing stage to simulate realistic crustal deformation in which fluid flow is induced under horizontal and vertical loads. Their results demonstrate that the tendency to hydrostatic pore pressures in carbonates leads to more stick–slip behaviour and thus a greater propensity for earthquake activity.

Geological observations and measurements made in the field and the laboratory have profound implications for our understanding of stress systems and their impact on rock deformation (e.g. **Gillespie & Kampfer 2017**). A particularly good example are the horizontal hydrofractures depicted in the cover photograph of this volume. Hydrofractures comprise mineralized fractures that open in response to high pore pressure and/or high differential stress. Zanella (2015) used modelling and worldwide examples to discuss physical conditions for the development of a type of hydrofracture termed 'beef'. By virtue of their horizontal attitude, the presence of beef indicates conditions in which, at least locally, fluid pressures exceed vertical (lithostatic) stress. Given that beef is usually confined to organic-rich shales, an intriguing possibility is that the origin of high pore pressure is the conversion of kerogens to hydrocarbons, leading to the possibility that the presence of beef can be used as a proxy for source rock maturation.

Hydrofracturing is a critical element of the fault-valve model first hypothesized by Sibson *et al.* (1988), also discussed by Myhill (2015). Meredith (2015) used experimental data to address an important implication of fault valving: that veins are critical to the re-sealing of pressure cells, thereby enabling them to build up to the next overpressure cycle. His data suggest that whilst sealing requires only for crack aperture to reduce, and thus occurs fairly rapidly, the process of crystal nucleation and growth on the fracture wall (healing) is slow – a 0.3 μm fracture aperture taking some 100 h to heal.

Application of geomechanics to oil and gas field developments has become increasingly important over the past 40 years, and geomechanics specialists are commonly recruited as permanent members of asset teams in larger development projects. Advances in the characterization and modelling of fractured petroleum reservoirs was a major theme that included case studies from the North Sea (e.g. Freeman 2015; **Wynn *et al.* 2017**) and from reservoir analogues in the Pyrenees (Gutmanis 2015). Another recurring theme of papers from the oil and gas industry was the impact that geomechanics understanding can have on planning wells. Batchelor (2015) examined how the complex relationship between geology and geomechanics presents challenging drilling conditions in the Eocene formations of the UK Central North Sea. The area is characterized by very weak stratigraphy (e.g. sand-in-sand injectites, semi-plastic mudrocks) in which the mud weight required to maintain wellbore stability often exceeds the fracture gradient.

Addis (2017) uses multiple case studies to demonstrate how stress fields may be complex, adjusting to changes in reservoir pressure over time (e.g. Brent Field, North Sea) and varying according to local contrasts in mechanical stratigraphy. For example, the Cusiana Field, Colombia is situated in an active thrust belt in the northernmost Andes and presented significant drilling challenges during development. *In situ* measurements indicated that vertical stress was much higher than would be predicted from Andersonian dynamics. Subsequent modelling revealed a highly compartmentalized stress system in which relatively strong reservoir sandstones acted as 'stress guides', refracting the minimum stress to a horizontal attitude. As a consequence of this greater understanding, the delivery of safer and more stable wells led directly to significant improvements in the performance of the field.

Geomechanics is a rapidly developing field that brings together a broad range of subsurface professionals seeking to use their expertise to solve current challenges in applied and fundamental geoscience. This introduction provides a flavour of the diversity and ingenuity of many of the contributions presented at the Geomechanics and Geology meeting, and hopefully encourages you to delve further into the volume. We hope that the papers herein provide a representative snapshot of the exciting state of geomechanics and establish it firmly as a flourishing subdiscipline of geology that merits broadest exposure across the academic and corporate geosciences.

We are grateful to all the poster presenters and speakers for contributing to a successful meeting. The efforts of authors and reviewers of papers contained herein led directly to this excellent volume and a worthy addition to the Geological Society's unrivalled set of special publications. We thank Tamzin Anderson, Jo Armstrong and Angharad Hills at the Geological Society Publishing House for helping to bring it to fruition. The staff of the conference office in Burlington House assisted us greatly in organizing the meeting itself. Mark Tingay is thanked for making his conference notes available. The meeting was sponsored generously by AGR, Badley Earth Sciences, Tracs, Tectonic Studies Group and The Petroleum Group.

References

ADDIS, M.A. 2017. The geology of geomechanics: petroleum geomechanical engineering in field development planning. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online June 28, 2017, https://doi.org/10.1144/SP458.7

ANDERSON, E.M. 1951. *The Dynamics of Faulting and Dyke Formation with Applications to Britain*. 2nd edn. Oliver & Boyd, Edinburgh.

BATCHELOR, T. 2015. Case studies of the complex relationship of geology and geomechanics in the Eocen formations of Quad 9 and Quad 15 based on 30 years' experience. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

BUBECK, A. 2015. ¿Como se lava? How representative are 'typical lavas' in volcano stability models? Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

COLLETTINI, C. 2015. The role of fluid pressure in frictional stability and earthquake triggering: Insights from rock deformation experiments. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

COUPLES, G. 2015. Some stressful realisations about the concept of stress in geomaterials. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

DESCAMPS, F., FAŸ-GOMORD, O., VANDYCKE, S., SCHROEDER, C., SWENNEN, R. & TSHIBANGU, J.-P. 2017. Relationships between geomechanical properties and lithotypes in NW European chalks. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 25, 2017, https://doi.org/10.1144/SP458.9

ENGELDER, T. 1992. *Stress Regimes in the Lithosphere*. Princeton University Press, Princeton, NJ.

ENGLISH, J.M. & LAUBACH, S.E. 2017. Opening-mode fracture systems: insights from recent fluid inclusion microthermometry studies of crack-seal fracture cements. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 24 2017, https://doi.org/10.1144/SP458.1

ENGLISH, J.M., FINKBEINER, T., ENGLISH, K.L. & YAHIA CHERIF, R. 2017. State of stress in exhumed basins and implications for fluid flow: insights from the Illizi Basin, Algeria. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 30, 2017, https://doi.org/10.1144/SP458.6

FETTER, M., MORAES, A. & MULLER, A. 2017. Active low-angle normal faults in the deep water Santos Basin, offshore Brazil: a geomechanical analogy between salt tectonics and crustal deformation. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 26, 2017, https://doi.org/10.1144/SP458.11

FREEMAN, B. 2015. Predicting sub-seismic fracture density and orientation: A case study from the Gorm Field, Danish North Sea. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

GILLESPIE, P. & KAMPFER, G. 2017. Mechanical constraints on kink band and thrust development in the Appalachian Plateau, USA. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online June 12, 2017, https://doi.org/10.1144/SP458.12

GRASSO, J.-R. 1992. Mechanics of seismic instabilities induced by the recovery of hydrocarbons. *Pure and Applied Geophysics*, **139**, 507–534.

GRIFFITH, A.A. 1921. The phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society*, **A221**, 163–197.

GULMAMMADOV, R., COVEY-CRUMP, S. & HUUSE, M. 2017. Geomechanical characterization of mud volcanoes using P-wave velocity datasets. *In*: TURNER, J.P., HEALY, D., HILLIS, R.R. & WELCH, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 25, 2017, updated version published online June 9, 2017, https://doi.org/10.1144/SP458.2

GUTMANIS, J. 2015. Reservoir characterization by integration of outcrop analog with in situ stress profiling of a fractured carbonate reservoir. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

HACKSTON, A. 2015. Faulting and friction of sandstones. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

HEIDBACH, O., RAJABI, M., REITER, K., ZIEGLER, M. & WSM TEAM 2016. *World Stress Map Database*

Release. GFZ Data Services, https://doi.org/10.5880/WSM.2016.001

Hubbert, M.K. & Willis, D.G. 1957. Mechanics of hydraulic fracturing. *Transactions of Society of Petroleum Engineers of AIME*, **210**, 153–168.

Jaeger, J. & Cook, N.G.W. 1979. *Fundamental of Rock Mechanics*. 3rd edn. Chapman & Hall, London.

Keranen, K.M., Savage, H.M., Abers, G.A. & Cochran, E.S. 2013. Potentially induced earthquakes in Oklahoma, USA: links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. *Geology*, **41**, 699–702.

Lahann, R.W. & Swarbrick, R.E. 2017. An improved procedure for pre-drill calculation of fracture pressure. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 30, 2017, https://doi.org/10.1144/SP458.13

Meredith, P.G. 2015. Strength recovery and vein growth during self-sealing of faults in Westerly granite. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

Myhill, D. 2015. Clumped isotope thermometry: A tool to further detail fluid processes in fault zones, a view from the South Pennines Orefield, Peak District, UK. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

Richardson, C.A. & Seedorff, E. 2017. Estimating friction in normal fault systems of the Basin and Range province and examining its geological context. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 25, 2017, https://doi.org/10.1144/SP458.8

Roberts, J.J., Wilkinson, M., Naylor, M., Shipton, Z.K., Wood, R.A. & Haszeldine, R.S. 2017. Natural CO_2 sites in Italy show the importance of overburden geopressure, fractures and faults for CO_2 storage performance and risk management. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online June 19, 2017, updated version published online June 23, 2017, https://doi.org/10.1144/SP458.14

Sibson, R.H. 2017. The edge of failure: critical stress overpressure states in different tectonic regimes. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 24, 2017, https://doi.org/10.1144/SP458.5

Sibson, R.H., Robert, F. & Poulson, K.H. 1988. High-angle reverse faults, fluid-pressure cycling, and mesothermal gold-quartz deposits. *Geology*, **16**, 551–555.

Tassone, D.R., Holford, S.P., King, R., Tingay, M.R.P. & Hillis, R.R. 2017. Contemporary stress and neotectonics in the Otway Basin, southeastern Australia. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 25, 2017, https://doi.org/10.1144/SP458.10

Tavener, E., Flottmann, T. & Brooke-Barnett, S. 2017. *In situ* stress distribution and mechanical stratigraphy in the Bowen and Surat basins, Queensland, Australia. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 24, 2017, https://doi.org/10.1144/SP458.4

Tingay, M. 2015. The present-day stress field in sedimentary basins. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.

Willis, B. 1891. *The Mechanics of Appalachian Structures*. United States Government Printing Office, Washington, DC.

Wynn, T.J., Kumar, R., Jones, R., Howell, K., Maxwell, D. & Bailey, P. 2017. Chalk reservoir of the Ockley accumulation, North Sea: *in situ* stresses, geology and implications for stimulation. *In*: Turner, J.P., Healy, D., Hillis, R.R. & Welch, M.J. (eds) *Geomechanics and Geology*. Geological Society, London, Special Publications, **458**. First published online May 30, 2017, https://doi.org/10.1144/SP458.3

Zanella, A. 2015. Load transfer, chemical compaction, seepage forces and horizontal hydrofractures within mature source rocks: evidence from theory, physical models and geological examples. Abstract presented at the Geology of Geomechanics Conference, 28–29 October 2015, Geological Society, London.