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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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depletion;
• 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 vs. 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) underestimated 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 geomechanical 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 $\sigma_2$. 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
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-scaling 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 \mu m 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.

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