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CSIRO submission

Independent Expert Scientific Committee (IESC) Explanatory Note – Characterisation and modelling of Geological Fault Zones

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Introduction

CSIRO welcomes the opportunity to provide comment on the *Independent Expert Scientific Committee (IESC) Information Guidelines Explanatory Note: Characterisation and modelling of geological fault zones.*

This submission comprises comments that have been prepared by CSIRO technical experts in the fields of mineral resources, energy and hydrology, in response to the three areas requested by the IESC:

- the technical content within the draft Explanatory Note. Are there any areas that are missing or not captured adequately?
- the relevance to your specific area of work and any views on its uptake and adoption; and
- potential options to increase uptake and adoption.

The Explanatory Note is an important contribution to understanding the groundwater behaviour around fault zones. It highlights the complex interplay between groundwater and aquifers, and the extent of physical deformation through faulting and subsequent chemical alteration of aquifer materials. Our response is provided in two parts:

- firstly, refining the description of these factors; and
- secondly, more detailed editorial comments.

CSIRO would be pleased to discuss any aspect of this submission with the IESC.

General comments

The Explanatory Note provides a comprehensive overview of geological fault features, their potential impact on groundwater in the context of coal seam gas (CSG) or large coal mine developments, their characterisation and representation in groundwater models.

The Explanatory Note is particularly relevant to other geological contexts where faults play the same role. This includes production operations for other commodities as well as research in the context of mineral and energy exploration in general. For instance, CSIRO recently published a study to address the "*greater computational burdens*" of some of the more advanced modelling methods listed in Section 4.3.1 (Poulet, Lesueur & Kelka, 2021).

Surface water

The Executive Summary states that the Explanatory Note "does not extend to considering surface water or highly detailed risk assessments or the consideration of environmental consequences for groundwater assets and GDEs". Consequently, surface water is largely excluded from the document. As streams and baseflow to streams are often an expression of a transmissive fault (e.g. Banks et al., 2019; Taylor et al., 2018), we recommend to also refer to the use of synoptic river surveys to detect faults. For example, in areas with poorly characterised subsurface and limited geophysical data, a surface water hydrochemistry and tracer survey (i.e. including parameters such as ^{222}Rn and ^{3}He) may provide very valuable insights into the presence and role of faults.

Likewise, spring hydrochemical and tracer surveys and hydrogeological conceptualisation should be part of the procedure described in the Explanatory Note, following for example methodology presented by Flook et al. (2020) in the Surat Basin in Queensland.

Baseline surveys

The Explanatory Note does not adequately highlight the importance of baseline hydrochemical and environmental tracer surveys. This limitation is apparent in all scenarios described, where hydrochemistry/tracers are omitted or described as a nice-to-have option rather than as a fundamental part of the fault zone characterisation, which has the potential to reduce the conceptual uncertainty and identify “unknown unknowns” such as faults that may not be picked up in data-sparse regions by limited geophysical surveys. In many cases, hydrochemical data such as measurement of groundwater methane concentrations may completely change the conceptualisation.

Geomorphology

Geomorphology (or tectonic geomorphology) is not mentioned in the Explanatory Note, although Section 2.1.3 does at a very high level relate to it. Streams often follow zones of structural weakness, so a detailed assessment of the stream network is essential. It is becoming increasingly evident that neotectonic activity occurs in many sedimentary basins throughout Australia, and that many of the major deep basement structures have been reactivated during recent geological times (e.g. Sandiford et al., 2020). The consideration of geomorphology is therefore very important.

Data and knowledge integration

There is a lack of emphasis on the critical importance of integrating multiple lines of evidence. For example, this is the case in the scenario table and the text describing the scenarios, where hydrochemistry and tracers as well as geomorphology are largely omitted.

Gas migration

Gas migration has not been considered as a potential negative impact resulting from CSG and large coal mining developments, and should be included in section 1.1. “why faults matter”. The release of methane and other hydrocarbon sources can be a source of contamination associated with CSG production as well as other more traditional oil and gas fields (as described by McIntosh et al. (2019)). The simple groundwater extraction from coal seams for gas production and aquifer depletion required for coal mine advancement have the potential to displace and promote CH_4 migration through faults, eventually reaching groundwater systems and other overlying assets (including surface water bodies). Further to this, faults may also provide conduits for gas migration before CSG production has started, i.e. natural gas migration. This should be assessed and discovered in baseline surveys but if missed can also cause the perception that production led to gas flow up faults.

In addition, CH_4 (concentrations and isotopic fingerprinting, including potentially compound specific isotope analysis) can also be used as a robust tracer to track possible connectivity via faults between the CSG beds and overlying aquifer systems in the vicinity of a proposed development. Fugitive emission surveys could provide insights into the vertical continuity of deeper faults to the surface.

Fault reactivation

There could be a stronger emphasis on the risk of fault reactivation. The Explanatory Note does mention fault reactivation but focuses on the static hydraulic problem and not geomechanics. We recommend additional sentences to highlight this risk:

- Mention recent past event (e.g. linked to geothermal shutdown events).
- In the list of data to acquire in the executive summary, mention acquisition of stress information around/within the fault to try and assess how close it is to criticality and reactivation.
- List the risks in section 4.5 even though the issue is out of scope and mentioned as an ongoing research area. The risk with faults is not only linked to displacements larger than aquitard thicknesses (leading to primary juxtaposition) but more subtle effects can arise from hydraulic changes (without subsidence) that could also trigger reactivation, including some linked to mining activities such as pumping, draining, injecting, flooding, etc.

Clay content of hanging- and footwall

This is an important parameter for estimating sealing capacity of a faults. In combinations with the displacement magnitude, this is usually applied to compute shale-gouge-ratios for estimating sealing capacities (i.e. clay smearing). The reference to '*Vrolijk PJ, Urai JL and Ketterman M 2016. Clay smear: review of mechanisms and applications. Journal of Structural Geology, 86: 95-152*' is present in the literature list but not referred to in the text. It is also important to account for the thickness of the displaced shale beds.

Damage zone

We suggest commenting on:

- where damage zones around faults develop (e.g. low-porosity, brittle rocks);
- how to estimate the width of the distributed damage in a fault zone (a very uncertain parameter);
- hydraulic connectivity of the damage zone leading to the hydrological linkage between fault zones that are not intersecting. Damage zones can also have different hydraulic properties in the hanging-wall and footwall, since different lithologies or different strain accumulation within the fault zone can result in asymmetric damage distributions.

Outcrop analogues

We suggest including information on how to evaluate the applicability of outcrop analogues, for example:

- that they must be evaluated based on existing geological knowledge as to whether fracture sets are likely to be present in the outcrop are also present at depth, in contrast to generations of fractures that are a consequence of exhumations; and
- consider varying fracture apertures, for instance, derived from length-aperture scaling.

Permeability anisotropy in strata adjacent to faults

Permeability anisotropy in strata adjacent to faults can have strong impact on flow patterns and can be expected when dealing with fractured aquifers or in the presence of finely laminated sediments that contain various thin horizontal clay layers. This can have a strong impact on how flow develops in the vicinity of adjacent fault zones.

Numerical simulation of fault related fluid flow

Questions that can be addressed using numerical simulation include determining the statistical parameters that can be obtained in the field to generate reliable stochastic fracture networks. Also, since fracture networks represent the entire geological history of a region, modelling the sealing of existing fractures and/or fault cores by secondary precipitates (overprinting relationships) or uplift can be used for fluid flow predictions. Furthermore, a mixed approach can account for different scales, for example homogenization/upscaling of fracture network in a model that explicitly contains the regional scale fault traces.

Explanatory Note structure

To improve the readability of the Explanatory Note, more illustrative diagrams could be incorporated, as some sections are quite dense with lots of technical jargon that could be more easily explained on the basis of one or several diagrams.

Some restructuring is also suggested as the key features of faults are introduced rather late in the document.

The case study examples are useful but need a more careful consideration of the system as a whole and not just the immediate surroundings of the mine/CSG development.

Specific comments

P7 ES – first paragraph: It would be fair to acknowledge that there are quantitative and qualitative impacts. Quantitative impacts like drawdown are primary impacts, but they can lead to secondary impacts such as changes in water quality when waters of different quality mix, and these should be mentioned.

P7 ES – second paragraph: the standard terminology for flow pathway is conduit. To avoid the term “both” sounding confusing, suggest alternative text: or a combination of a barrier (to horizontal flow) and a conduit (upward or downward flow via the damage zone).

P8 ES – consider adding a dot point on “in situ stress, field orientation and magnitude of stresses, pore fluid pressure and relationship to fault orientation (dip and strike) and geometry”.

P9 Table 1 – add “laterally and vertically” to dot point “flow parallel to faults may be enhanced in fault damage zones that contain fractures” in Scenario B.

P9 Table 1 – add “baseline geochemistry and pressure data from above and below aquitard” in fifth column of Scenario A2.

P9 Table 1 – add “Fault/fracture development due to subsidence or fluid pressure change in fifth column of Scenario A.

P9 Table 1 – add dot point “baseline geochem/pressure data” in the fourth column against scenario C.

P11 Section 1. Introduction: typo: covers

P11 Section 1. Introduction: typo: a Standard

P11 Section 1.1 Why do faults matter? “fault movement and hydraulic head changes”: there are some good cartoons in Bense et al. 2013 that illustrate these features.

P12 Fig 1: Suggest to combine this with an image displaying K across the fault zone to show how the different conceptualisations translate in K-profiles. (e.g. Fig 5d & e from Bense et al. 2013)

P13 Second bullet point: add reference to Zhang et al. 2018 (on the geomechanical impact of depressurization of coal beds on fault geomechanical stability)

P13 suggest defining “pilot point methodology”

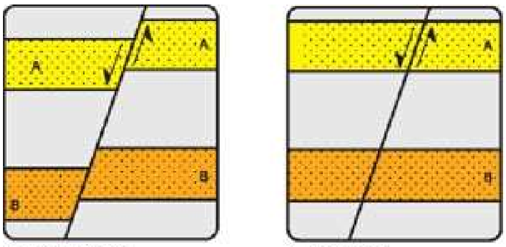
P13 suggest considering injection as possibly in scope in the third dot point (e.g. waste water injection or hydraulic fracturing).

P14 second line from top: dependent on … and any regulatory thresholds, i.e. maximum drawdown of x m...

P14 Fig. 2: This diagram could also include the impact of a CSG development on fault reactivation (i.e. the geomechanical impact of depressurization of coal beds on fault geomechanical stability). Could add external box at LHS with arrow arriving in "Characterise fault zone.." (i.e. modified fault zone permeability and flow).

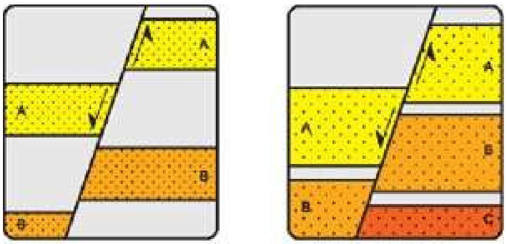
P14 Fig. 2: With reference to the box “identify potential fault pathways”, consider local hard data of fault, e.g. from well; this should represent the best way to characterise fault zone hydraulic properties (rather than derived from a pump test); is that included in “characterise aquitard/aquifer”?

P16 Section 2.1.1 Geologic stratigraphy. Suggest to include one or more illustrative images of the effect of faulting on stratigraphic sequences, e.g. see example below, noting this is a schematic in 2D for illustrative purposes only and it is the 3D fault zone structure that is critical to determine (e.g. Allan, 1989).



1. Partial self juxtaposition

2. Full self juxtaposition



3. non juxtaposition (juxtaposition seal)

Cross reservoirs juxtaposition

Fig 1. Schematic diagram of various juxtaposition orientations (Neele et al. 2012).

P 17 Fig. 3 Suggest to add the approximate range of fault damage zones as flow in conduit faults is mainly via such damage zones with dimensions of much larger than those of the fault core.

P 17 Fig. 3: We recommend to add a caveat that this figure does not distinguish between *vertical* and *horizontal* scales, and that especially vertical scales of flow in most applications are probably limited to about 1-2 km, while horizontal scales of flow typically are much larger than 10 km.

P18 Section 2.1.2: We suggest that fault-related products and resources such as Frogtech's Seebase (https://www.geognostics.com/oz-seebase-2020), which are freely available for download, should be specifically mentioned here, as they provide a valuable resource on mapped faults in Australia. Likewise, products such as magnetics and radiometric images/digital data, which are available for large parts of Australia from state geological surveys and Geoscience Australia, should be mentioned as they can provide valuable insights into presence of faults (especially deep basement faults which may have been reactivated later).

P18 section 2.1.3: This is a very important section which should include reference to the analysis of additional investigative methods and data sources such as the drainage network configuration, as streams often follow the zones of weakness and this combined analysis can help to identify concealed structures. Considering these additional data sources can provide valuable insights into neotectonics. When considered together with other data sources (e.g. Frogtech's Seebase), it can help to assess where reactivation of deep basement faults has occurred (and thus, where pathways linking deep gas reservoirs with shallow aquifers or surface water systems may exists). Case studies of this kind of "tectonic geomorphology" are presented for example by Hodgkinson et al. (2007), Gleeson & Novakowski (2009) and Sandiford et al. (2020).

P18 section 2.1.3 Reference to GA and other datasets: these are great examples – we suggest there could be more of these.

P18 Section 2.1.5 Sporadic or punctual geological mapping (i.e. not covering the entire area due to access issue or vegetation-relief) will inform on the possible presence of faults (i.e. discontinuities) by evaluating mapped stratigraphic units/layers distribution, dip azimuth and associated small scale (intra) deformation. With limitation of subsurface data, field mapping - although time consuming - can contribute valuable information.

P19 Section 2.1.6 With reference to the statement "Direct observation of faults and fractures…" it is worth emphasising here that the direct observation of fault (offset >10m) is often challenging in core or borehole image log data (and in most wireline log) and such geological faults (that may be barely in seismic data due to resolution limitation for displacement < 15-20m) might often and easily be missed or misinterpreted as these represent meter-scale to decimeter-scale objects (i.e. a meter-scale fault zone with complex internal geometry dipping 60 deg and intersected by a borehole will represent a meter-scale zone of complex deformation possibly even incorporating some undeformed lenses.)

P19 Section 2.1.7 Seismic information is very important, but also very expensive. Whilst there are seismic data and images available in many areas of exploration, they are often (especially where exploration for CSG/hydrocarbons occurs) acquired to focus on the deep subsurface (i.e.> 300-400 m depth). However, a key question in hydrogeology is often if deep basement structures continue and form potential pathways to shallow aquifers or the surface. With modern data processing techniques, it is possible to re-process existing seismic survey data to provide better insights into the geometry of the shallow subsurface.

P19 Section 2.1.8 Airborne electromagnetics are very useful, but also very expensive, and may not always be feasible. Depending on the purpose and spatial scale of the study, it is worth mentioning that targeted ground-based TEM surveys can also be very useful, so perhaps this section could be a bit broader than just AEM. Likewise, other techniques such as hydraulic tomography are also a viable technique to characterize fault zone hydrogeology at smaller scales. This technique should be included. Some additional references are Cardiff et al. (2013), Zha et al. (2015, 2016).

P19 Section 2.1.8 Also airborne magnetics (and its first vertical derivative) will provide good indications of shears and faults (e.g. Munday et al. 2020).

P19 Section 2.1.8 missing reference: Lawrie et al. 2012

P19 Section 2.1.9 “For example, if a distinct step in level is observed in the subsurface, a fault is inferred.” This is a very important point that highlights the significance of general structural geological expert knowledge, particularly when supported by other lines of evidence on inferring fault occurrences in sparse data situations. Often, 3D geological models do not represent fault displacements, as it requires considerable resources that are sometimes beyond what can be achieved in projects. Nevertheless, the presence and considerable displacement can be clearly inferred from such 3D geological models (e.g. shown in Evans et al. (2020)). We recommend this section should include a discussion around the degree of uncertainty associated with fault inferences from indirect data other than geophysics (e.g., baseline gas monitoring, hydrochemistry and tracer distribution along flowpaths). More details and citation to articles would benefit this section as for large scale assessments this has been proven to be a contentious issue. In such data-sparse settings, other techniques such as stream hydrochemical and tracer surveys (e.g. Taylor et al., 2018) can also be very useful.

P19 Section 2.1.10 The sentence “Dissimilar measurements either side of a fault are a line of evidence that a fault zone is a potential barrier to groundwater flow across the fault zone” needs to further state that flow across the fault is not necessarily zero. The head drop across the fault is inversely related to the hydraulic conductivity of the fault: the smaller the K the larger the resistance to flow across the fault and hence the larger the head drop. For very small K values flow may be close to zero. This highlights the need to make clear that the term “barrier” covers a wide range of flow conditions including causing small head drops to very large head drops.

P20 Section 2.1.11 Water chemistry and tracers: So far the guideline only considers investigation (geological, geophysical, hydrochemical and tracer) and modelling *prior* to development. It is equally important to monitor *during* development, which allows to confirm or falsify the conceptualisation and modelling prior development. Here environmental tracers are extremely useful, in all scenarios. This is because environmental tracers, also in cases where no hydrochemical distinction between different aquifers is possible, allow characterisation of the origin of a water mass (in terms of age and infiltration conditions). Especially tracers for young groundwater can be an early warning indicator for GW influx to CSG or large coal mining projects along pathways that during the EIA have either not been sufficiently detected or underestimated in their importance. If, for instance, the pumps that keep an open pit mine dry (or that dewater a CSG field) at the beginning of development sample very “old” water (e.g. 0 pmc in ^{14}C) but ^{14}C content increases during development or even tritium shows up, then this could be an indication of fast pathways from the surface to the project that had been insufficiently considered, or for which transmissivities have been underestimated. In a similar way, an increase in ^{4}He may indicate an underestimated pathway from a deeper formation, since this tracer is the most sensitive tracer for older and deeper groundwater. Also, there is not much discussion and worth thereby ascribed to baseline data collection, or indication this might be necessary, for 'thresholded' cases, i.e. based on likelihood of there being unidentified pre-existing faults (type of geology?) or creation of faults by proposed or other activities.

P20 Section 2.1.11 Water chemistry and tracers: It is not clear how conflicting information should be approached, e.g. if tracer data creates questions where previous geophysical data and conceptual models suggested there would be no faulting concern. Question: are the tracer examples/recommendations overly skewed towards those that might indicate upwards flow (with helium and radon the only tracers mentioned by name.), i.e. are we missing what might indicate downwards flow such as contribution of freshly recharged water to deeper aquifers? Noting this relates to the previous comment on use of young water tracers to track downward flows during the development.

P20 Section 2.1.11 Water chemistry and tracers: Compared to other sections of the document, this section is lacking detail and should be expanded significantly to better describe what types of hydrochemical and environmental tracers could be used to support fault inference and connectivity pathways identification. Furthermore, water chemistry and environmental tracers are presented here and in the scenario table as "nice-to-have" options. For example, it states that "if data on coal related gases are available, they are clearly relevant to fluid flow, and can provide valuable constraint information on the current or possible future groundwater flow (Iverach 2015)." However, baseline hydrochemical and tracer data are essential (and also cost-effective) tools to identify and characterise faults and their hydrogeological role. Parameters such as methane concentrations and isotopes are also critical to determine throughout project life cycles if any changes (e.g. reactivation) in the role of the fault has occurred throughout a project life cycle. Without adequate baseline data, this is impossible. The authors rightly give a lot of credit to Allan (1989) throughout this document. However, the sentence "the beginnings of these efforts to integrate data can be found in the foundations of fault flow analysis (Allan 1989)" seems misplaced and is considerably overselling this in a section on water chemistry and environmental tracer studies, as the study by Allan 1989 does as far as we could see not make any reference to water chemistry or tracers whatsoever.

P20 Section 2.1.11 Lawrie 2014: missing reference

P20 Lo et al. 2014: missing reference

P21 Section 2.2 This section could have been introduced sooner as several of the terms are used in earlier sections without proper introduction/definition.

P21 Section 2.2.1 define 'normal or reverse fault'

P22 Section 2.2.6 There are excellent diagrams available that illustrate these various concepts and how they relate to flow (barrier/conduit).

P23 Shipton reference is not in reference list

P23 It may be worth referencing additional papers on fault scale such as

Walsh, J.J., Nicol, A., Childs, C., 2002. An alternative model for the growth of faults. Journal of Structural Geology 24, 1669– 1675.

Walsh, J.J., Bailey, W.R., Childs, C., Nicol, A., Bonson, C.G., 2003. Formation of segmented normal faults: a 3-D perspective. J. Struct. Geol. 25 (8), 1251–1262.

Walsh, J.J., Watterson, J., 1988. Analysis of the relationship between the displacements and dimensions of faults. Journal of Structural Geology 10, 239– 247.

Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J., Withjack, M.O., 2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. J. Struct. Geol. 32 (11), 1557–1575.

Schlische, R.W., Young, S.S., Ackermann, R.V., Gupta, A., 1996. Geometry and scaling relations of a population of very small rift-related normal faults. Geology 24, 683– 686.

P23 With reference to fault transmissibility, while Manzocchi and Sperrevik are probably the most likely used methods, there are others such as Jolley et al., 2007

P24 triangle diagrams are also referred as 'clay-smear type panel' or 'triangle plot' or 'juxtaposition diagram' (Bentley and Barry, 1991; Knipe, 1997)

Bentley, M.R., Barry, J.J., 1991. Representation of fault sealing in a reservoir simulation: cormorant block IV, UK North Sea. Soc. Petrol. Eng. Reprint 22667, 119–126.

Knipe, R.J., 1997. Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. AAPG Bull. 81, 187–195.

P24 juxtaposition is primarily described and illustrated by Knipe, R.J., 1997. Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. AAPG Bull. 81, 187–195.

P24 both the Allan map and the juxtaposition diagram are only the very first level of investigation into across fault flow. Once the possibility for juxtaposition between aquifers is established, there is a need to ask if the interface between these units (i.e. aquifers) allows or prevents flow by quantifying the membrane seal capacity. Whilst the Explanatory Note is not an how-to manual, we suggest addressing (at least superficially) the issue of the strength of the fault seal as this has been a field extensively studied in siliciclastics over the last 40 years or so.

Fault-rocks in classic siliciclastic petroleum provinces display a range of hydraulic properties and capillary threshold pressures that are mostly related to wall-rock lithologies (i.e. volume of clay or shale), confining stress, fault displacement and deformation mechanism (Yielding, 2012). Fault seal between reservoir-sand compartments can result from clay smear into the fault plane; from cataclasis or the crushing of sand grains to produce a low permeability fault gouge of finer grained material or from diagenesis, when preferential cementation along an originally permeable fault plane may remove porosity and define a hydraulic seal (Watts, 1987; Knipe, 1992). The Shale Gouge Ratio algorithm (SGR) (Yielding et al., 1997) uses the clay distribution through the wall-rocks and the fault displacement, to define a proxy of the average clay content of a fault zone. Calibration based on buoyancy pressure show that the onset of membrane fault seal for oil occurs at an SGR value of about 0.2 (Bretan et al., 2003). Outcrop and experimental data also suggest that an SGR value of about 0.2 corresponds to a transition to complete and continuous clay smear in fault zones (Yielding, 2002).

P24 explain blue coloured sections of Figure 5

P25 Section 3: This section could be renamed to "Geological framework/conceptualization considering/including structural features" (or similar to this effect). There should be a representation (graphical) and description of the physical system with emphasis on the integration of multiple lines of evidence obtained from multiple data sources described in Section 2.1. The use of hydrochemistry and environmental tracers integrated with the physical system characterization (geometric) should be expanded further. Such integration work can result in significant reduction of the uncertainty associated with the understanding of the role of faults.

P25 Section 3.1, can this be extended to address the typical causes for fault to act as barriers and give direction on how to conceptualise and assess.

P25 Section 3.1.1 There are at least 3 conceptualisations that need discussion: faults as barriers, conduits and barrier/conduits. Only the first is discussed here. Please add the next two.

P25 Section 3.2 point 5 - Along fault (or up fault flow or fault parallel flow) can be associated with structural permeability related to open fractures in damage zone next to a fault core / major slip surfaces or due to a stress-related event (i.e. reactivation, earthquake) that activates or "critically-stresses" faults and fractures. This later mechanism has been often cited as more likely to be fluid conduits whereas inactive or non-critically stressed faults are thought more likely to act as barriers (e.g. Sibson, 1987; Anderson et al., 1994; Barton et al., 1995; Sanderson and Zhang, 1999; Wiprut and Zoback, 2000; Zoback and Townend, 2001). While you address the permeability of fractures in the damage zone when you discuss DFN and EPM you don't seem to address the geomechanics of fault (zones) that (theoretically) controls the stress state of a fault and if/when a fault is critically stressed; this seems to fit your scenario D where reactivation is driven by differential movement.

We suggest addressing fault geomechanics and techniques to characterise it (i.e. when plotted on a Mohr diagram, faults lying above the failure envelope are reactivated and likely to be conductive (Barton et al., 1995; this is supported by evidence showing that seal breach by fault reactivation represents a critical exploration risk for hydrocarbons in many petroleum provinces (Sibson, 1996; Abrams, 1996; Kaluza and Doyle, 1996; Dewhurst and Jones, 2002; Dewhurst et al., 2002, Gartrell and Lisk, 2005; Langhi et al., 2010)). However, as said before the fault geomechanics might not be directly relevant for CSG and large coal mining considering the shallow depth and possible poor lithification (this approach probably best fits harder consolidated sediments and hard rocks). Bense and Pearson (2006) touch on the matter " In strongly lithified sedimentary rocks, dilation can create open fracture networks enhancing the permeability in the damage zone by several orders of magnitude [Evans et al 1997] ... "Rawling et al. [2001] argue that in poorly lithified sedimentary deposits a fault zone will not contain open-fracture networks,"

Abrams, M. A., 1996. Distribution of Subsurface Hydrocarbon Seepage in Near-Surface Marine Sediments: Aapg Memoir 66, 1–14.

Anderson, R., Flemings, P., Losh, S., Austin, J., Woodhams, R., 1994. Gulf of Mexico Growth Fault Drilled, Seen As Oil, Gas Migration Pathway: Oil & Gas Journal, 92, 97–104.

Barton, C.A., Zoback, M.D., Moos, D., 1995. Fluid flow along potentially active faults in crystalline rock. Geology 23 (8), 683–686.

Dewhurst, D. N., and R. M. Jones, 2002. Geomechanical, Microstructural and Petrophysical Evolution in Experimentally Reactivated Cataclasites: Application to Fault Seal Prediction: Aapg Bulletin, V. 86, 1383–1405.

Dewhurst, D.N., Jones, M.R., Hillis, R. R., Mildren, S.D., 2002. Microstructural and Geomechanical Characterisation of Fault Rocks from the Carnrvon and Otway Basins: Australian Petroleum Production and Exploration Association Journal, 42, 167–186.

Gartrell, A. P., Lisk, M., 2005. Potential New Method For Paleostress Estimation By Combining 3d Fault Restoration And Fault Slip Inversion Techniques: First Test On The Skua Field, Timor Sea, In P. Boult And J. K. Kaldi, Eds., Evaluating Fault And Cap Rock Seals: Aapg Hedberg Series 2, 23–36.

Kaluza, M. J., Doyle, E. H., 1996. Detecting Fluid Migration In Shallow Sediments, Continental Slope Environment, Gulf Of Mexico: Aapg Memoir 66, 15–26.

Langhi, L., Zhang, Y., Gartrell, A., Underschultz, J.R., Dewhurst, D.N., 2010. Evaluating Hydrocarbon Trap Integrity during Fault Reactivation Using Geomechanical 3d Modelling: An Example from the Timor Sea, Australia. Aapg Bulletin 94, 567-591.

Sanderson, D.J., Zhang, X., 1999. Critical stress localization of flow associated with deformation of well-fractured rock masses, with implications for mineral deposits. [in special issue: Fluid Flow and Fracture Systems] Geol. Soc. London Spec. Pub. 155, 69-81.

Sibson, R.H., 1987. Earthquake rupturing as a mineralizing agent in hydrothermal systems. Geology 15, 701-704.

Wiprut, D., Zoback, M.D., 2000. Fault Reactivation and Fluid Flow along a Previously Dormant Normal Fault in the Northern North Sea. Geology, 28, 595-598.

Zoback, M. D., Townend, J., 2001. Implications of Hydrostatic Pore Pressures and High Crustal Strength for the Deformation of Intraplate Lithosphere. Tectonophysics, 336, 19–30.

P25 3.3 Conceptual scenarios: It is not clear how thinking/models would change from Scenario B to Scenario C or D, i.e. if the stochastic modelling of potential repercussions show it is warranted, the process should be shifted to C or D. Although these shifts might occur through dialogue with IESC, practicality of application of the document by proponents/agents should be of high consideration, i.e. so planning of resources to the activities might be better calibrated early in processes to avoid a drip-feed situation that seeks to answer 1 question at a time and might be a poorer use of resources

P27 Table 1 Scenario A-1: site-based evidence: Potentiometric maps per hydrostratigraphic unit are easy to construct and may provide complementary data about negligible impact of a few faults on flow. Similar maps based on salinity or temperature may be equally useful to display presence or absence of anomalies.

Scenario A-2: as above for scenario A-1

Scenario B – fault flow groundwater phenomena: flow may also be upward or downward along the fault plane, with dewatering/depressurisation changing the gradient and flow regime

P27-28 Table 1 – Scenario A2 points “Vertical fault offset (throw) is smaller than the thickness of aquitards” and “Faults are therefore unlikely to form” seems to exclude strike-slip faults and especially intersections which have potential vertical fracture zones. This is especially important where the horizontal stress at present day is the maximum principal stress.

Scenario A2 also seems to assume normal or reverse faults only.

Scenario C – There is regular reference to drawdown effects, i.e. reduction of pore pressure and increased effective stress. Fit-for-purpose geomechanical models would be best to assess such effects.

Scenario D – with reference to the point “analysis of in situ stress, and the effect that evacuation may have on stress and the change in stress requires fault reactivation” – this is also critical for subsurface developments, e.g. depressurization during coal seam gas production, but is not addressed. Stress field, pore pressure change, and compaction/subsidence/fault reactivation are closely linked and can occur during subsurface development. This is also potentially relevant to other scenarios in the table.

Scenario D – the point in second column “This scenario is most likely to apply to underground mines but could also occur in open cut mining and CSG” – we suggest change to “does” apply to CSG not just “could”.

P29 first bullet point: change “rapid water movement” to rapid lateral or upward/downward water movement

P30: McCallum et al. 2018: missing reference

P31 third last paragraph – could link to example in Figure 6

P33 Section 4.3.2 History matching and other locations where history matching is mentioned with reference to environmental tracers: History matching is correctly regarded in the guideline as a standard technique to create more reliable forecasts of models. However, we recommend to explicitly mention that history matching or at least a thorough conceptualisation of the GW flow system must happen *at the same timescale* as that covered by the forecast. Furthermore, often the pre-development state can no longer be established (e.g. with hydraulic head measurements), because land clearing and groundwater use have changed the natural state prior to the first groundwater assessment for the CGS or large coal mining development (for instance in the Surat Basin, OGIA 2019). The value of environmental tracer measurements is that they provide a window into the past since they provide information on past events according to the time scale they operate on, e.g. decades for tritium, centuries for ^{39}Ar and millennia for ^{14}C and ^{4}He. Therefore, in all discussed scenarios, environmental tracers are a necessary source of data for the history matching of the pre-development state. We therefore recommend, regardless of the scenarios, to integrate where possible environmental tracers to underpin the pre-development conceptualisation. This then provides a solid basis for testing any changes due to CSG or large coal mining developments.

P33: Cui et al. 2018: missing reference

P34 Section 4.3.2 could be useful to provide examples of parameters to be matched, i.e. water production, pressure variation, head?

P 34 section 4.4.1 Dual permeability models: Suggest to list public domain or low-cost codes that have dual porosity/permeability capability, such as Tough2, HYDRUS2/3D, MODFLOW-2005 (through the definition of a new package, the Conduit Flow Process, that incorporates multi-porosity and multi-permeability components of groundwater flow); MT3DMS is implemented with an optional, dual-domain formulation for modelling mass transport.

P33 section 4.4.1: Illustrative conceptual diagrams such as below would help the reader understand the intricacies of the approach.

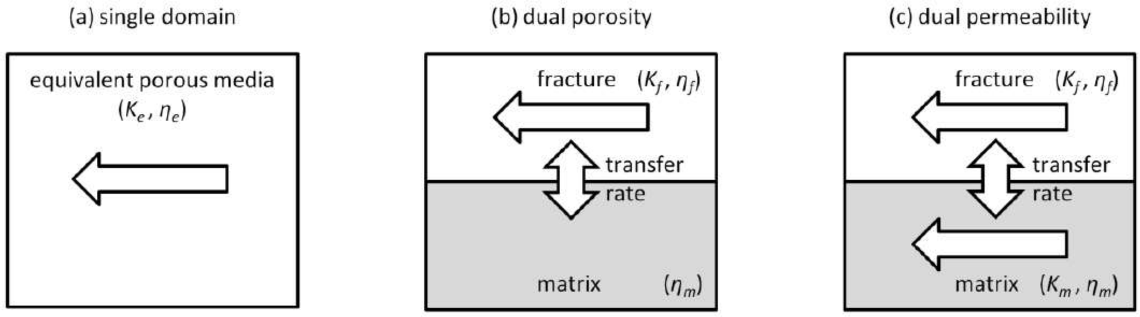


Figure 12. Comparison of (a) single domain, (b) dual porosity and (c) dual permeability approaches to groundwater flow [after Šimůnek and van Genuchten (2006)]. Symbols are defined as follows: K_e = equivalent hydraulic conductivity; η_e equivalent porosity; K_f = fracture conductivity; η_f = fracture porosity; η_m = matrix porosity; and K_m = matrix conductivity.

P35 Section 4.4.2: It is great to see that the note points out that continuum-based methods of history matching may not work for DFN models. It also suggests that regional sampling-based methods are important for uncertainty analysis. A few references for methods/tools should be added here.

P35 Section 4.5: For large coal mining, the stress disturbance to the surrounding rocks can be significant. See Guo et al. (2012) and Zhu et al. (2014). This section should be further expanded to emphasize the importance of the stress-induced hydraulic field change and to mention that it should be considered in groundwater modelling where possible.

P35 section 4.5 see example from Zhang et al. 2018 for geomechanical effects on faults in Australian coal basin

P35 Section 4.5 – consider adding more detail about how these models are applied and an example.

P36 Section5.2.2 – point 3 “Representative fault triangle diagrams….” – these weren’t explained earlier in the document; consider adding a diagram to explain the concept.

P37 Section 5.2.3 – Regarding point 3, an examination of known natural gas seepage along faults would be a useful baseline where this is known in a given area.

P40 check if the references to Figure 6 are supposed to refer to Figure 7

P41 – Definition of “strike” – note that the strike degrees are not necessarily as stated in the table, it depends on the direction of the feature (i.e. strike is 90 degrees clockwise from the dip direction).

P27 and 46: General comment to the scenario examples in the table and the text. It is widely acknowledged that the characterisation of faults requires the integration of multiple lines of evidence. However, the table and the examples do not necessarily reflect this adequately. For example, there is limited reference to the use of hydrochemistry/tracers as well as to geomorphology. As the table may provide a “cookbook” for stakeholders when characterising faults in future studies, it is critical to revise the table and the examples significantly to highlight the need for integrated approaches that consider multiple lines of evidence. Also, in the table and the scenario examples and throughout the document there is no mention of the need to collect baseline on hydrochemistry or tracers of groundwater and surface water. Some scenarios assume that there are no faults or that there is no breached aquitard. However, based on sparse subsurface data, there may indeed be faults that have not been identified. Therefore, other independent data sources may provide important insights.

P47 third bullet point: How should sub-seismic (or undetectable) faults be treated in this scenario?

P48 – Example scenario A-2: “nil chance of cross-fault flow if there is not juxtaposition of coal seam with aquifer”: suggest this should be worded less black and white but more gradual. e.g. if the aquitard is 100m thick but has vertically moved by 90 m along the fault, the risk of getting flow through that aquitard is definitely much higher, even though the upper and lower aquifer are not juxtaposed. -> i.e. it may be better to treat this case as scenario C.

P48 - “Vertical fault offset (throw) is less than the thickness of the aquitard and thus does not compromise the integrity of the aquitard” is a valid argument but such condition may still impact the *horizontal* flow conditions. Indeed: a 15-m-thick aquifer my experience restricted flows if a 100-m-thick aquitard has a 20-m-throw. We also suggest to include a discussion on the role of the heave, not just throw. Again, this is also restricting the discussion to normal and reverse faults. However, conjugate strike slip faults for example may show little vertical offset, but the intersection of those faults can create a vertical conduit resulting from enhanced dilation/fracturing in that area.

P48 second last paragraph: Formation-scale evidence of lack of flow can be derived from helium profiles (e.g. Smith et al. 2018).

P51 Example scenario B and C: these examples disregard where recharge/discharge happens and the implications that may have on the problems studied, especially, if a fault is less permeable and partly acts as a barrier, keeping the downstream part from recharging if too much is extracted. A good understanding of groundwater flow through the system as a whole from recharge to discharge areas is important to do a correct assessment, but in remote areas, this understanding is generally not very strong. That’s one of the major areas where tracers would be useful. Here is an example to illustrate this point of needing a stronger focus on the system as a whole and not just the immediate surroundings of the mine: In Fig. 8, Part 1, there is a strong head gradient towards the left, west of the “West Fault”, suggesting that the left part of Aquifer A gets most of its recharge from east of the light blue thin line. However, if that is the case, the profile in Part 3 is wrong because the groundwater level at the left boundary would drop rather than increase once the longwall mining starts (and probably already in Part 2 as well).

P53 – Example scenario B: site-based evidence: suggest to add tracer data to complement pumping test (e.g. sampling for helium up flow and down flow as a test of conceptual models).

P55 – “small relay ramps” is not defined in the glossary

P58 – Example scenario C: Tracers can detect current downward/upward flow but cannot predict flow after depressurization. Models can predict that, but how sensitive is a model calibration based mostly on heads, if currently the deeper aquifers have little head variation because there is not much flow in them? Can tracers help to get a better constrained calibration? (e.g. in Scenario C)

P58 - Example scenario C: “extensive site-specific pumping tests…” are listed before tracers in Scenario C., would this order of priority be the best use of resources in the case of faults? Pumping tests have the advantage of observing flow characteristics and deriving some hydraulic properties, but if the primary question is one of faults, might not tracers offer some more efficient use of resources? In the “Suggested Approaches” column lumping of tracers and pumping tests creates mis-impression.

P62 With reference to the opening sentence (“the fourth scenario in Table 1….”), this could occur for CSG also with reservoir compaction and pore pressure depletion.

P62 second paragraph – consider making this point clearer in the introduction of the report.

P62 While Underschultz summarised the approach, it might be useful to point towards some of the legacy and fully developed papers such as:

Bretan, P., Yielding, G., Mathiassen, O.M., Thorsnes, T., 2011. Fault-Seal Analysis for CO2 Storage: An Example from the Troll Area, Norwegian Continental Shelf. Petroleum Geoscience. 17 2011, 181–192.

Mildren, S.D., Hillis, R.R., Dewhurst, D.N., Lyon, P.J., Meyer, J.J., Boult, P.J., 2005. Fast: A New Technique for Geomechanical Assessment of the Risk of Reactivation-Related Breach of Fault Seals. In: Boult, P. & Kaldi, J. (Eds) Evaluating Fault and Cap Rock Seals. Aapg Hedberg Series, 2, 73–85.

Morris, A., Ferrill, D.A., Henderson, D.B., 1996. Slip Tendency Analysis and Fault Reactivation. Geology 24 (3), 275–278.

Wiprut, D., Zoback, M.D., 2000. Fault Reactivation and Fluid Flow along a Previously Dormant Normal Fault in the Northern North Sea. Geology, 28, 595-598.

Wiprut, D.J. and Zoback, M.D., 2000. Constraining the full stress tensor in the Visund field, Norwegian North Sea: application to wellbore stability and sand production. Int. J. Rock Mech. Min. Sci., 37: 317-336.

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Allan, U. S. (1989). Model for hydrocarbon migration and entrapment within faulted structures. American Association of Petroleum Geologists Bulletin, 73, 803-811.

Banks E., M. Hatch, S. Smith, J. Underschultz, S. Lamontagne, A. Suckow, D. Mallants 2019. Multi-tracer and hydrogeophysical investigation of the hydraulic connectivity between coal seam gas formations, shallow groundwater and stream network in a faulted sedimentary. J. Hydrol. 578 November 2019, 124132 https://doi.org/10.1016/j.jhydrol.2019.124132.

Bisdom, K., Bertotti, G. and Nick, H.M., 2016. The impact of different aperture distribution models and critical stress criteria on equivalent permeability in fractured rocks. Journal of Geophysical Research: Solid Earth, 121(5), pp.4045-4063. https://doi.org/10.1002/2015JB012657

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Flook, S., Fawcett, J., Cox, R. et al. A multidisciplinary approach to the hydrological conceptualisation of springs in the Surat Basin of the Great Artesian Basin (Australia). Hydrogeol J 28, 219–236 (2020). https://doi.org/10.1007/s10040-019-02099-5

Gleeson T and Novakowski K (2009) Identifying watershed-scale barriers to groundwater flow: Lineaments in the Canadian Shield. Geological Society of America Bulletin 121(3-4), 333-347. Doi: 10.1130/b26241.1.

Guo, H., Yuan, L., Shen, B., Qu, Q., Xue, J., 2012. Mining-induced strata stress changes, fractures and gas flow dynamics in multi-seam longwall mining. Int. J. Rock Mech. Min. Sci. 54, 129–139.

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