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Publication Date

2008-06-02

Peer reviewed

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3 **Screening and ranking framework (SRF) for geologic CO₂**
4 **storage site selection on the basis of HSE risk**

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15

1 **Abstract** A screening and ranking framework (SRF) has been developed to evaluate potential
2 geologic carbon dioxide (CO₂) storage sites on the basis of health, safety, and environmental (HSE)
3 risk arising from CO₂ leakage. The approach is based on the assumption that CO₂ leakage risk is
4 dependent on three basic characteristics of a geologic CO₂ storage site: (1) the potential for primary
5 containment by the target formation; (2) the potential for secondary containment if the primary
6 formation leaks; and (3) the potential for attenuation and dispersion of leaking CO₂ if the primary
7 formation leaks and secondary containment fails. The framework is implemented in a spreadsheet in
8 which users enter numerical scores representing expert opinions or published information along with
9 estimates of uncertainty. Applications to three sites in California demonstrate the approach.
10 Refinements and extensions are possible through the use of more detailed data or model results in place
11 of property proxies.

12
13 **Keywords:** Screening, Ranking, Geologic CO₂ Storage, Site Selection, HSE

14

15 **Introduction**

16 In order to reduce the possibility that carbon dioxide (CO₂) storage projects will result in health, safety,
17 and environmental (HSE) impacts due to CO₂ leakage and seepage, it is essential that sites be chosen to
18 minimize HSE risk. This is particularly important for early pilot studies for which leakage and seepage
19 for any reason could be perceived as a failure of the general approach of geologic CO₂ storage. Apart
20 from site-specific operational choices once a given CO₂ injection project is underway, the best way to
21 avoid unintended leakage and seepage is to choose a good site at the outset. To this end, a spreadsheet-
22 based Screening and Ranking Framework (SRF) for evaluating multiple sites on the basis of their
23 potential for HSE risk due to CO₂ leakage and seepage has been developed (Oldenburg 2005). Some
24 key terminology used in the HSE SRF is presented in Table 1.

25

26 **Background and Motivation**

27 Existing approaches to risk assessment of fluids injected into geologic formations include the Features,
28 Events, and Processes (FEP) scenario approach (e.g., Savage et al. 2004; Wildenborg et al. 2005),

1 Probabilistic Risk Assessment (PRA) (e.g., Rish 2005), and related approaches (e.g., Bowden and Rigg
2 2004). In the FEP/scenario approach, a comprehensive list of FEPs is developed and codified in a
3 database that is then used to define scenarios for leakage and seepage, or any other performance-
4 affecting event. Modeling is then used to evaluate the consequences of that scenario in terms of CO₂
5 impact due to long-term high concentrations at key receptors. The performance-affecting FEPs may
6 have subjective probabilities associated with them, and from the product of consequence as simulated
7 in the scenario and probability as assigned to the FEPs, risk can be calculated. In the probabilistic
8 approach of Rish (2005) developed for Class I hazardous waste injection wells, probabilities of events
9 and distributions of properties are input and the likelihood of various detrimental events is calculated.
10 Bowden and Rigg (2004) invoke a quantitative probabilistic approach that involves innovative risk
11 measures applied to key performance indicators. This approach is applicable to screening and ranking
12 of multiple sites, while the FEP and PRA approaches are most applicable to risk assessment of a single
13 site. However, the Bowden and Rigg (2004) approach involves a level of detail (e.g., an expert panel)
14 beyond what is likely going to be practical for initial screening and ranking of numerous sites.

15
16 The SRF approach presented here is aimed at an early screening and ranking stage of site selection. In
17 the early stages, there are likely to be numerous sites up for evaluation, as there are numerous
18 objectives of geologic CO₂ storage. For example, the various objectives of proximity to CO₂ source,
19 proximity to existing pipelines, compatible current land use, favorable geologic structure, etc., will not
20 all be met at any one site, resulting in numerous sites put forward for evaluation that all have strengths
21 but also weaknesses. At this early stage, site characterization data will be sparse or non-existent, and
22 time and money will not be available for in-depth site characterization. What is needed for screening
23 and ranking of a large number of sites on the basis of HSE risk is a quick, inexpensive, and consistent
24 framework to identify a small number of the better candidate sites, for which more in-depth site
25 characterization and risk assessment analyses can be undertaken with more detailed and quantitative
26 approaches. As more data become available, additional criteria and selection frameworks may be
27 applied, such as those evaluating injectivity and capacity.

28

1 **SRF Approach**

2 **Theory and Design**

3 The HSE impacts of CO₂ that are of concern are caused by high concentrations of CO₂ in the near-
4 surface environment where humans, plants, and other living things reside. For example, if a large flow
5 rate of gas with a high concentration of CO₂ occurs over a small area, the resulting large flux of CO₂
6 can cause persistent high CO₂ concentrations in soil gas which in turn can lead to root respiration
7 limitations and corresponding plant stress or death (Farrar et al. 1995; Qi et al. 1994). In aquifers, high
8 CO₂ concentrations can in some circumstances lead to leaching of heavy metals that could adversely
9 affect water quality (Wang and Jaffe 2005). In the above-ground environment or in basements and
10 houses, high CO₂ concentrations in air can lead to health effects ranging from dizziness to death in
11 humans and other animals (Benson et al. 2002).

12
13 There is a wide variety of recognized potential pathways for leakage from deep geological formations
14 to the near-surface environment, e.g., abandoned wells and permeable fault zones. However, for nearly
15 every leakage pathway, there is also potential for secondary entrapment at higher levels in the system.
16 In addition, CO₂ leakage along any of the pathways involves the potential for attenuation or dispersion
17 of a CO₂ plume during migration. To minimize HSE effects, it is necessary that injected CO₂ either
18 (1) does not leak from the storage formation, (2) is secondarily trapped if leakage does occur, or (3) is
19 attenuated or dispersed if leakage occurs (e.g., by mixing in the atmosphere, or by uptake and mixing
20 by groundwater or surface water) and if there is ineffective secondary entrapment.

21
22 With this understanding, the HSE SRF was developed to evaluate three basic characteristics of a
23 geologic CO₂ storage site:

- 24
- 25 (1) Potential of the target formation for long-term containment of CO₂;
 - 26 (2) Potential for secondary containment if the primary target site leaks; and
 - 27 (3) Potential of the site to attenuate and/or disperse leaking CO₂ if the primary formation leaks and
28 secondary containment fails.

29

1 The SRF is implemented in a spreadsheet designed to evaluate these three basic characteristics through
2 user input of Property values, which define Attributes, which define the Characteristics, as shown in
3 Table 2. The spreadsheet does simple arithmetic and averaging to produce a score for each basic
4 characteristic along with the associated uncertainty. The values and properties entered by the user
5 combine to represent proxies for site characterization data and model analyses that may not be
6 available, as shown in the far-right column of Table 2. For example, there is a Primary Containment
7 attribute called Primary Seal for which lithology is a proxy for permeability and porosity. The idea
8 here is that permeability and porosity may not have been measured but that the known lithology of the
9 seal provides a fair representation of these properties. This proxy could be replaced at a later stage of
10 site study or operation by data or model results that represent seal effectiveness in more detail, e.g., by
11 quantitative prediction of CO₂ flux. In this way, the SRF can be extended and updated as site
12 characterization occurs to include more quantitative measures of performance.

13

14 The SRF relies on input by a user who either already knows something about the sites, has opinions
15 about the sites based on general information, or who has gained knowledge about them from published
16 reports, maps, and papers. The expected users of the SRF are geoscientists and/or hydrologists with
17 some general knowledge of the sites and/or access to limited published information about the sites in
18 reference books or maps. It is expected that one user or group of users will evaluate all of the
19 candidate sites in a given screening or ranking exercise, thereby ensuring a measure of consistency in
20 each assessment. Simplicity and transparency are key design features of the SRF spreadsheet.

21

22 Although the SRF was developed based on experience with geology and CO₂ storage rather than with
23 the formality of decision analysis, the approach falls loosely under the category of multi-attribute
24 utility theory (Keeney 1980; Keeney and Raiffa 1976). The three scores that are evaluated for each site
25 are proxies for combinations of impact and likelihood (i.e., risk) of leakage, secondary entrapment, and
26 attenuation. The assessment made in the framework is based on four classes of information: (1) site
27 characteristics which are defined by (2) attributes, which are defined by (3) properties which are
28 defined by (4) values input by the user.

29

1 **Spreadsheet**

2 The SRF is implemented in a spreadsheet with three simple worksheets (one for evaluation of each of
3 the three basic characteristics) and a summary page. There are three categories of entries. First, the
4 user can control the importance of a given property through the specification of weighting factors for
5 each of the j properties of each attribute. The weighting factors (w_j) are normalized by the spreadsheet
6 as

7
$$\sum_j w_j = 1 \tag{1}$$

8 so any arbitrary scale can be used. The weighting option allows the user great latitude in applying
9 his/her judgment to the evaluation. For example, if the user feels strongly that caprock seal thickness
10 is the overriding property controlling leakage and seepage, then a large number can be assigned for the
11 weight of that property and the caprock thickness value will dominate the assessment of the attribute
12 Primary Seal. An example of the Primary Containment worksheet is shown in Figure 1, in which light
13 blue cells are those expecting user input. The two other worksheets (Secondary Containment, and
14 Attenuation Potential) are similar but with appropriate cells for the respective properties as given in
15 Table 2. As shown in Figure 1, the weight of the seal thickness property is assigned a value of 10 out
16 of a total of 21 making approximately one-half of the weight of the primary seal attribute and its
17 uncertainty rest on the seal thickness value. For comparing sites in the process of screening or ranking,
18 the use of different weighting factors for the properties of different sites should be carefully
19 considered. In the example cases presented below, constant weighting factors are used for consistency.

20
21 The second step of the SRF spreadsheet is to assign a numerical value a_j to the properties based on
22 suggestions in pop-up comments in the spreadsheet. Examples of property values can be seen in
23 Figure 1 for the Rio Vista case. The numerical values are chosen as integers ranging from -2 (poor) to
24 +2 (excellent) with 0 considered neutral (neither good nor bad). Broad ranges of values are offered for
25 various conditions in the pop-up comments to guide the user in selecting an integer between -2 and +2.
26 Real numbers can also be used in cases when the user feels it is warranted.

27

1 The third thing the user does is enter a value for the confidence with which each property is known (2
2 is very certain, 0.1 is highly uncertain). This confidence information will be carried along and plotted
3 with attribute assessments for each of the three characteristics.

4
5 From this user input, a variety of averaged quantities is generated by the spreadsheet. The fundamental
6 calculation the spreadsheet does is to add up the weighted property assessments and average them
7 across the attributes to arrive at a score for each of the three fundamental characteristics. This is done
8 for each of the j properties shown in Table 2, and then averaged over the i attributes. There are three
9 attributes (primary seal, depth, and reservoir) for Primary Containment, two attributes (secondary seal,
10 shallower seals) for Secondary Containment, and four attributes (surface characteristics, groundwater
11 hydrology, existing wells, and faults) for Attenuation Potential. Thus, $i = 3$ for Primary Containment, i
12 $= 2$ for Secondary Containment, and $i = 4$ for Attenuation Potential (see Table 2)). For site n , the score
13 (S) for each characteristic is an average over the i attributes of the weighting factors (w) and values (a)
14 of the j properties which can be written as

$$15 \quad S_n = \frac{1}{i} \sum_1^i \left[\sum_j w_j a_j \right]_i \quad (2).$$

16 For site n , the overall qualitative measure of confidence (C) for each characteristic is an average over
17 the i attributes and j properties and values is averaged over the i attributes as follows,

$$18 \quad C_n = \frac{1}{i} \sum_1^i \left[\frac{1}{j} \sum_j c_j \right]_i \quad (3)$$

19 where c_j is the confidence with which each property is known. It is important to emphasize that the
20 relative assessments of different sites are not necessarily linearly related to their relative physical
21 behaviors. For example, a site that scores a 1.5 for the primary containment characteristic does not
22 necessarily leak 50% less than a site that scores 1.0 for primary containment. In fact, such sites could
23 be orders of magnitude different in their ability to contain CO₂. The assessment scores simply
24 represent relative rankings of the sites without indicating absolute performance.

25

1 **Additional Points**

2 The SRF is designed so that it can be applied to multiple sites with limited data. Many of the
3 properties and values of attributes that the user will input into the SRF spreadsheet are actually proxies
4 for uncertain and undetermined quantities that could eventually be measured or modeled with
5 additional site characterization effort. However, because of the lack of data that will be the norm for
6 most site-selection processes, uncertainty has been made a fundamental input and output of the SRF
7 that is kept separate from the scores for the characteristics. Uncertainty in the SRF is defined broadly
8 and includes parameter uncertainty (e.g., how well-known a given property is) and variability (e.g.,
9 how variable a given property is).

10

11 The methods behind the SRF differ from other approaches such as the Features, Events, and Processes
12 (FEP) scenario approach (e.g., Savage et al., 2004; Wildenborg et al. 2005), and the probabilistic
13 approach (e.g., Rish 2005). The FEP/scenario approach is laborious at the site-selection stage and
14 requires significant site-specific information to be carried out effectively. The Probabilistic Risk
15 Assessment (PRA) approach (Rish 2005) is similar to the FEP/scenario approach and makes use of a
16 Failure Modes and Effects Analysis (FMEA) coupled to event and fault tree development. Estimating
17 the frequency of occurrence of very rare events makes these approaches difficult to apply.

18 Furthermore, these quantitative approaches rely on accurate distributions of properties, something that
19 will be difficult at best to estimate for multiple sites especially during the early phases of site selection.

20 The approach of Bowden and Rigg (2004) is preferred for screening and ranking over FEP and PRA,
21 but still appears to demand more information and expense than will be available at the level of
22 screening more than a few sites.

23

24 In summary, the SRF spreadsheet was designed to provide a qualitative and independent assessment of
25 each of the three basic characteristics through an evaluation of the properties of their various attributes.

26 In the SRF approach, there is no modeling and simulation nor are probabilities assigned. The rationale
27 behind the SRF is that detailed site-characterization information, especially for pilot CO₂ injections, is
28 not expected to be sufficient to undertake a FEP/scenario analysis at the site-screening stage, nor to
29 assign probabilities for a probabilistic analysis. Instead the SRF uses qualitative pieces of information,
30 for example as gleaned from general reports or an expert's knowledge of an area, as proxies for

1 potential FEPs and consequences combined. By this approach, the analysis is greatly simplified and
2 includes explicitly the level of confidence that the user assigns to the assessments as a primary output.
3 In short, the SRF is designed to answer the question, “From a choice of several potential sites, and
4 based on existing information, which site has the lowest HSE risk?”
5

6 **Screening and Ranking Framework Examples**

7 **Rio Vista Gas Field**

8 The Rio Vista Gas Field is located in the Sacramento Basin of California, approximately 75 km
9 northeast of San Francisco. In production since 1936 from reservoirs in an elongated dome-shaped
10 structure extending over a 12 km by 15 km area, the majority of gas has come from the Domengine
11 sands in fault traps at a depth of approximately 4500 ft (1400 m) with sealing by the Nortonville shale.
12 Details of the field can be found in Burroughs (1976) and Johnson (1990). Information from these
13 published sources along with our general knowledge allowed us to fill in values in the SRF spreadsheet
14 assuming it would be used as a geologic CO₂ storage site. As shown in the Summary worksheet and
15 attribute graph for Rio Vista of Figure 2, the high attribute score reflects the very effective primary
16 containment expected at Rio Vista. Secondary containment is not expected to be very effective as
17 sealing formations above the Nortonville shale are largely absent. However, the attenuation potential
18 is excellent at Rio Vista due largely to steady winds and flat topography. As shown in Figure 2,
19 confidence in the attribute assessments is quite high for subsurface and surface characteristics at Rio
20 Vista due to its long history of gas production. The high score and certainty suggest that Rio Vista Gas
21 Field is a good candidate for geologic CO₂ storage. The colored curves on the attribute graphs are
22 arbitrary functions that separate poor, fair, and good regions of the graph. The concave-down shape of
23 these curves indicates that increasing certainty in site attributes improves the score of a site even if
24 attribute assessment stays the same. This is consistent with the idea that if even if the attributes of a
25 site do not change as you learn more about it, the site becomes more desirable because the more you
26 know about a site, even if it is more knowledge about deficiencies, the better you can engineer around
27 the deficiencies.
28

1 **Ventura Oil Field**

2 The Ventura Oil Field taps reservoirs in young folds and fault traps in marine sediments of the
3 tectonically active coastal area northwest of Ventura, California. The primary structure is the Ventura
4 Anticline, a dramatic fold that is visible in outcrops in the deeply incised canyons of the area. Natural
5 oil seeps and tar are widely found in the area. Using geological information from published references
6 (Sylvester and Brown 1988; Harden 1997) and our own knowledge of the site, we assigned values in
7 the SRF appropriate for the Ventura Oil Field. As shown in Figure 2, the Ventura Oil Field ranks
8 lower than the Rio Vista Gas Field. The oil accumulations at Ventura indicate that good traps exist,
9 but the evidence of widespread oil seepage along with the lack of significant natural gas accumulation
10 suggest that pathways to the surface also exist. As for secondary containment, some of the oil
11 reservoirs in the area are quite shallow, suggesting that secondary containment may occur, however
12 there is a high degree of uncertainty, and variability especially in light of the abundant seepage. As for
13 attenuation potential, the Ventura area is highly dissected with steep canyons that do not promote
14 dispersion of seeping CO₂. There is also considerable population to the southeast that could be
15 exposed to seeping CO₂. Therefore, attenuation potential is also judged worse at Ventura than at Rio
16 Vista.

17
18 **Mammoth Mountain**

19 The SRF was also applied to a naturally leaking site for verification purposes. Mammoth Mountain,
20 California, is a 200,000 year-old dormant volcano with active springs, geothermal anomalies, and CO₂
21 seepage that has killed native trees and also skiers who fell into enclosed depressions in the snow. For
22 this purely academic analysis of the potential HSE effects of deliberate CO₂ injection, we assume the
23 area under consideration is comparable to Rio Vista and Ventura in terms of size by considering the
24 entire Mammoth Mountain area. Using published information from (Farrar et al. 1995; Sorey et al.
25 1999) we filled in values and properties of the SRF spreadsheet. Many of the properties are given the
26 lowest values because they simply do not apply at Mammoth Mountain. For example, as evidenced by
27 the extensive seepage, we have concluded that there is no effective seal present, and therefore scored
28 those properties with the lowest values. Other properties are not very well known and we scored them
29 accordingly. As shown in Figure 2 (right-hand side), the Mammoth Mountain site scored badly as
30 expected in primary and secondary containment. The site does better on attenuation potential because

1 it is fairly windy and the population is relatively sparse. Nevertheless, the SRF spreadsheet
2 demonstrates that Mammoth Mountain would not be a good place to store anthropogenic CO₂ in the
3 subsurface.
4

5 **Discussion**

6 The preceding demonstration of the SRF cannot formally be called a validation since no one has
7 injected CO₂ into any of these sites and evaluated the three basic characteristics directly. Nevertheless,
8 the results are consistent with our general knowledge and expectation of these three sites. The benefit
9 of the SRF is that this knowledge and expectation is now formally expressed in a way that others can
10 review, criticize, revise, or affirm. There is a large degree of arbitrariness introduced in the SRF by
11 allowing the user to weight the importance of various site properties. In the above examples, the
12 weighting factors were the same for all three analyses. In the case that weighting factors are changed
13 for the various sites under comparison, it will be more difficult to defend direct comparisons.

14 Nevertheless, the transparency of the system and simplicity will allow a critic or reviewer to alter the
15 weighting functions and do the analysis again to compare the effect. Group efforts with multiple
16 people evaluating the same sites may prove especially useful because this would tend to capture a large
17 range of opinions while simultaneously bringing uniformity to comparisons between the different sites.

18 As with any tool, misuse is of course possible and the SRF assumes an underlying integrity of the
19 users. Because of the transparency and simplicity of the approach, there is little possibility to hide
20 abuses.
21

22 Extensions of the framework are possible. First, as more data become available, distributions rather
23 than single values could be input by the user where such distributions are known. This would add a
24 component of variability to the outcome, and potentially better represent the range of performance of a
25 site rather than a worst-case, best-case, or average performance. In addition, proxy scores for site
26 properties such as lithology could be replaced by measurements or modeling results of permeability
27 and porosity during a more detailed site characterization phase.
28

1 **Conclusions**

2 A framework for screening and ranking candidate sites for geologic CO₂ storage on the basis of HSE
3 risk has been developed to evaluate three basic characteristics of a geologic CO₂ storage site. The
4 framework allows users to arbitrarily weight and assign uncertainty to the properties of the attributes of
5 the basic characteristics to evaluate and rank two or more sites relative to each other. We emphasize
6 that this is a screening and ranking risk assessment tool intended to guide the selection of the most
7 promising sites for which more detailed risk assessment would be carried out at a later stage of the
8 project. Example applications of the framework show that comparative evaluations of prospective sites
9 with limited characterization data can be accomplished based on potential for CO₂ leakage and seepage
10 and related HSE risk. Testing and further development of the SRF are underway.

11

12 **Acknowledgments**

13 This paper benefitted from the helpful comments of two anonymous reviewers and guest editors Jens
14 Birkholzer and Chin-Fu Tsang. Earlier drafts were reviewed by Thomas E. McKone and Marcelo J.
15 Lippmann (LBNL). I thank Larry Myer and Sally Benson (LBNL) for support and encouragement.
16 This work was supported in part by WESTCARB through the Assistant Secretary for Fossil Energy,
17 Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL),
18 and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC03-
19 76SF00098.

20

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1 Figure Captions

2

3

4 Figure 1. Example worksheet from the SRF spreadsheet for the characteristic Primary Containment.

5

6

7 Figure 2. Summary SRF worksheet and three graphs for the example sites.

8

1
2
3
4

Tables

Table 1. Terminology related to CO₂ HSE screening and ranking framework.

| Term | Definition |
|--------------|---|
| Leakage | Migration in the subsurface away from the primary containment formation. |
| Seepage | Migration across a boundary such as the ground surface or into surface water. |
| Near-surface | Plus or minus 10 m from the ground surface. |
| Flux | Transport per unit area per unit time (e.g., kg m ⁻² s ⁻¹). |
| Flow | Transport per unit time (e.g., kg s ⁻¹) |
| Plume | Large relatively concentrated volume of CO ₂ either in the subsurface or above ground. |
| Impact | Consequences or effects of a given high CO ₂ concentration on health, safety, and the environment. |
| Risk | Product of probability of occurrence of an event and its impact. |

5
6

1

2 Table 2. Characteristics, attributes, properties, and proxies.

| Characteristics | Attributes (<i>i</i>) | Properties (<i>j</i>) | Proxy for.. |
|-------------------------------------|-------------------------|---|--|
| Potential for primary containment | Primary seal | Thickness Lithology Demonstrated sealing Lateral continuity | Likely sealing effectiveness Permeability, porosity Leakage potential Integrity and spillpoint |
| | Depth | Distance below surface | Density of CO ₂ in reservoir |
| | Reservoir | Lithology Permeability and porosity Thickness Fracture or primary porosity Pore fluid Pressure Tectonics Hydrology Deep wells Fault permeability | Likely storage effectiveness Injectivity, capacity Areal extent of injected plume Migration potential Injectivity, displacement Capacity, tendency to fracture Induced fracturing, seismicity Transport by groundwater Likelihood of well pathways Likelihood of fault pathways |
| Potential for secondary containment | Secondary seal | Thickness Lithology Demonstrated sealing Lateral continuity Depth | Likely sealing effectiveness Permeability, porosity Leakage potential Integrity and spillpoint Density of CO ₂ |
| | Shallower seals | Thickness Lithology Lateral continuity Evidence of seepage | Likely sealing effectiveness Permeability, porosity Integrity and spillpoint Effectiveness of all seals |
| Attenuation Potential | Surface characteristics | Topography Wind Climate Land use Population Surface water | CO ₂ plume spreading Plume dispersion Plume dispersion Tendency for exposure Tendency for exposure Form of seepage |
| | Groundwater hydrology | Regional flow Pressure Geochemistry Salinity | Dispersion/dissolution Solubility Solubility Solubility |
| | Existing wells | Deep wells Shallow wells Abandoned wells Disposal wells | Direct pathway from depth Direct pathway Direct pathway, poorly known New fluids, disturbance |
| | Faults | Tectonic faults Normal faults Strike-slip faults Fault permeability | Large permeable fault zones Seal short-circuiting Permeable fault zones Travel time |

3