

Prediction of Fluid-Rock Interactions in CCS Fields – An Integrated Approach Using Basin Modeling and Geochemistry*

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Abstract

The long-term integrity of geological CO₂ storage benefits from the sequestration of CO₂ in mineralized form. However, mineral reactions are very slow and difficult to simulate in laboratory experiments or by geochemical modeling. Natural CO₂ fields provide a great opportunity to study the fluid-rock interactions on geological time scales in true, complex geological systems. The Werkendam natural gas field contains > 72% CO₂. This natural analogue is representative of many potential storage sites in the Netherlands. The insights obtained from the natural analogues can be used to calibrate geochemical models. To be able to distinguish between normal diagenetic reactions and reactions related to CO₂, an analogue field was selected containing only minor amounts of CO₂ but have the same reservoir type, i.e. stratigraphy and age, at the same present-day depth. To ensure that past burial and diagenetic history of the two fields are comparable, basin modeling was applied to the areas. Based on the integration of basin modeling and petrographic analysis, we succeeded in assessing long-term mineral reactions related to CO₂ presence.

References Cited

Koenen, Marielle, Laura J. Wasch, Marit E. van Zalinge, and Susanne Nelskamp, 2013, Werkendam, the Dutch natural analogue for CO₂ storage – Long-term mineral reactions: Energy Procedia, v. 37, p. 3452-3460.

Koenen, Marielle, Laura J. Wasch, Svenja Waldmanna, and Sven van der Gijp, 2014, Observed CO₂-induced reactivity in Werkendam gas field, the Dutch storage analogue: Energy Procedia, v. 63, p. 2985-2993.

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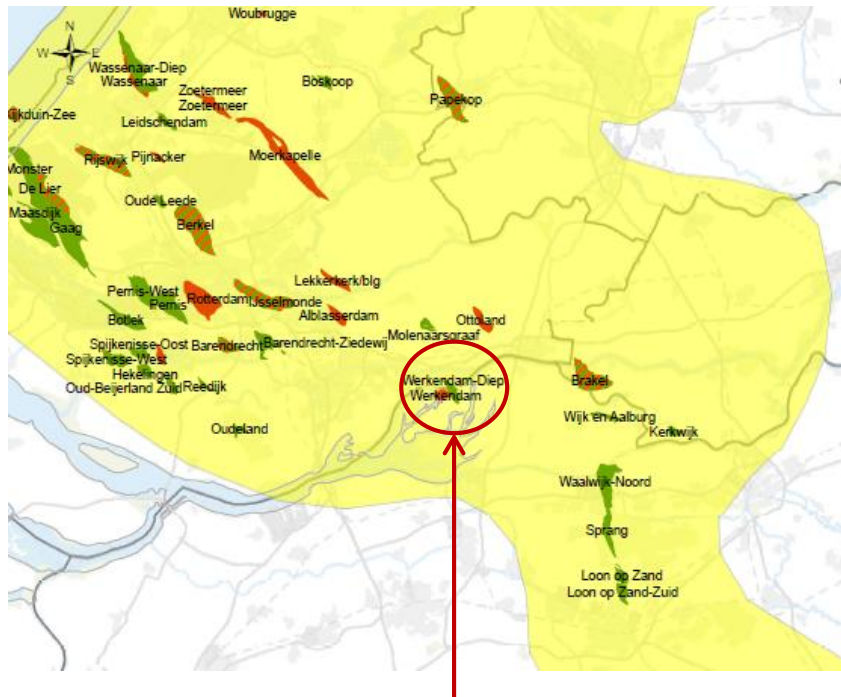
TNO innovation
for life

Netherlands organisation for applied science

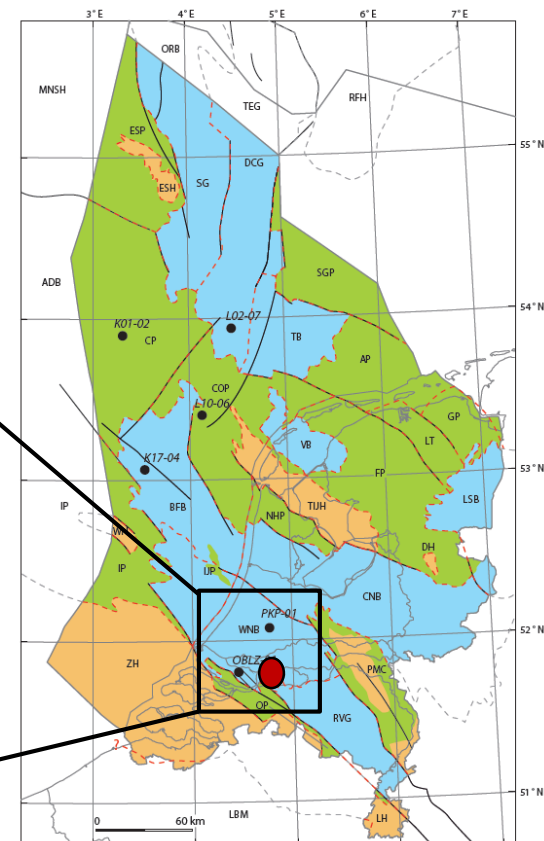
- › **Geological storage** is studied as one of the potential solutions to limit greenhouse gas emissions
- › **Impact of CO₂ injection** into a reservoir affects geochemical equilibrium
- › Experimental studies of geochemical reactions limited time and spatial scales
- › Geochemical modeling cover larger timescales, however
 - › modeling ~ simplification of complex geological system
 - › modeling ~ subject to uncertainties
- › **Natural CO₂ fields** provide insight into long-term geochemical interaction between CO₂, formation water and reservoir rock

NATURAL CO₂ FIELD WERKENDAM

- › Werkendam natural analogue (WED) → 72% CO₂
- › Located near Rotterdam, the Netherlands
- › At boundary between West Netherlands Basin and Roer Valley Graben

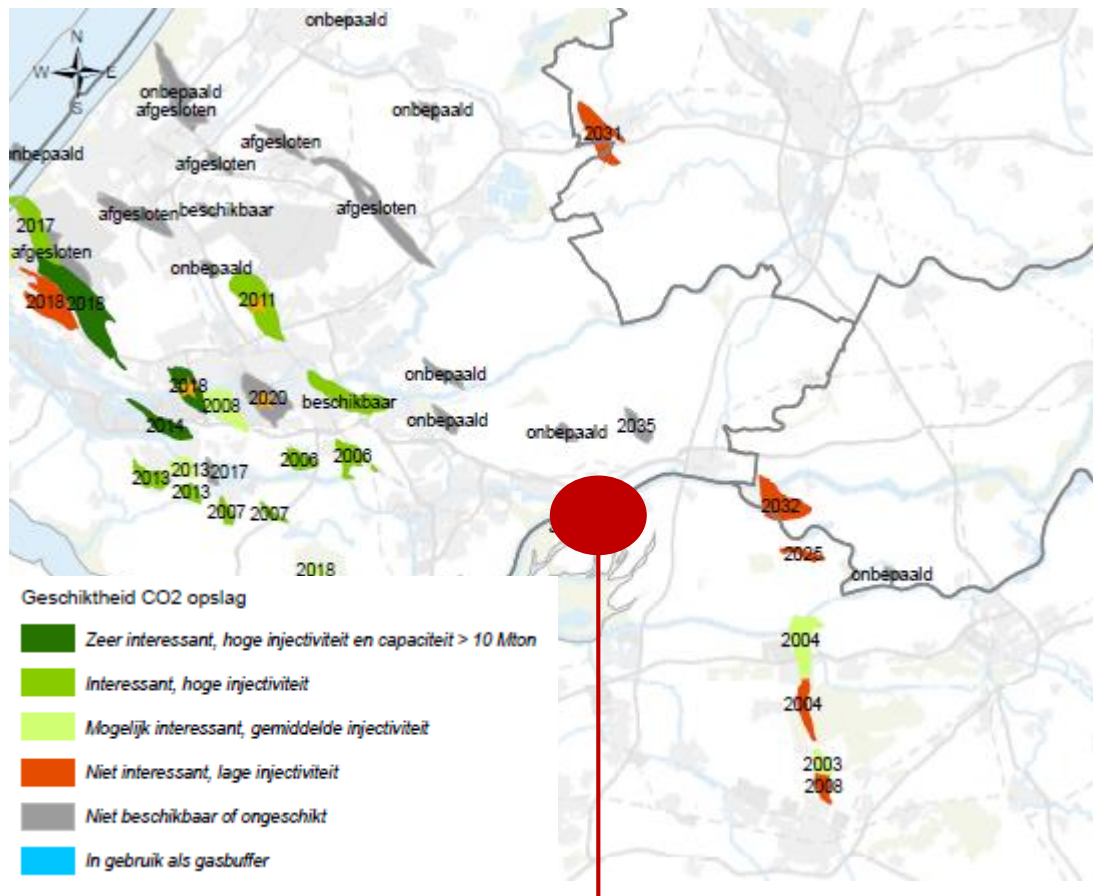


CO₂-rich field



GAS FIELDS & CO2 SEQUESTRATION

Inventory of possibility for CO2 sequestration in
gas fields (status 2012)

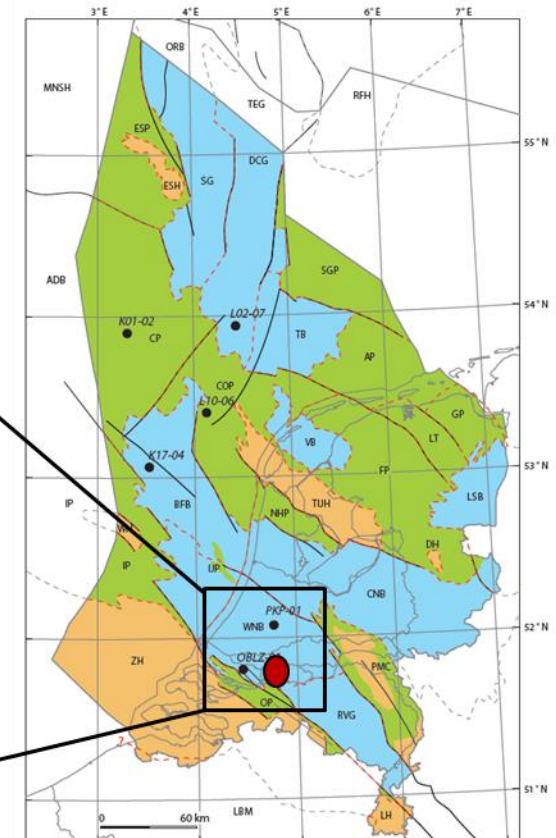
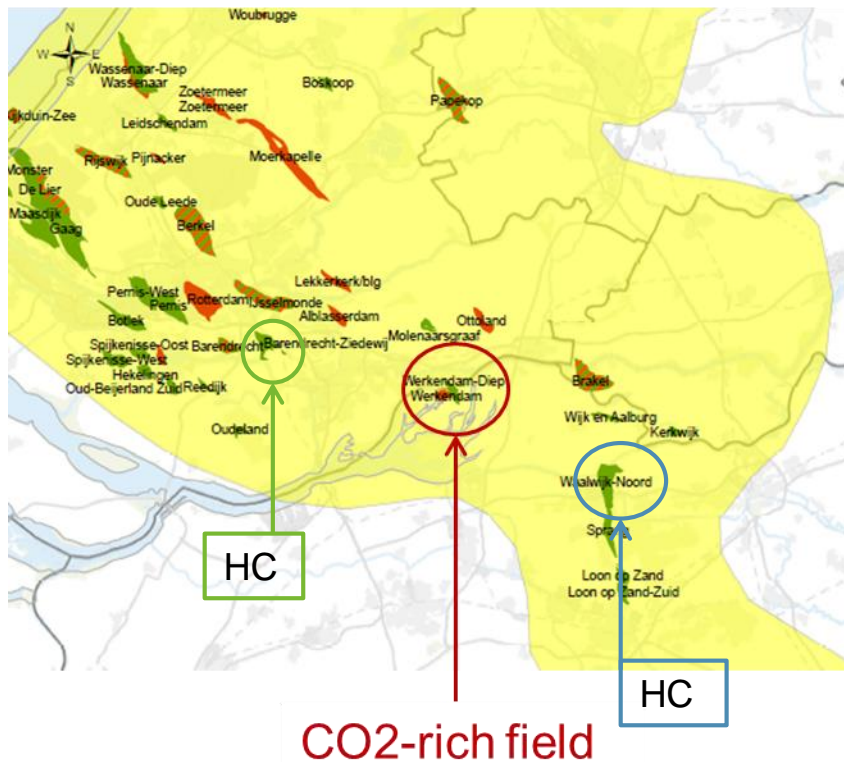


CO2-rich field

CASE STUDY

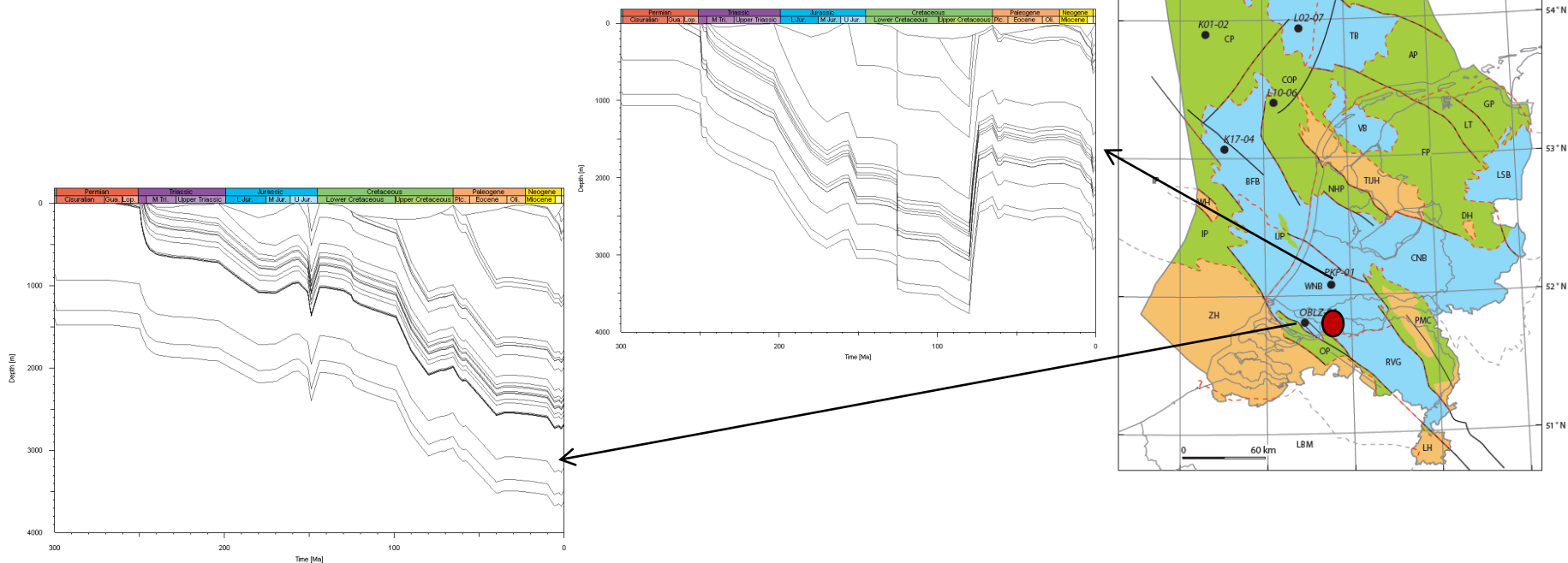
› Studied fields:

- › Werkendam natural analogue (WED) → 72% CO₂
- › Waalwijk-Noord (WWN) → HC
- › Barendrecht-Ziedewij (BRTZ) → HC



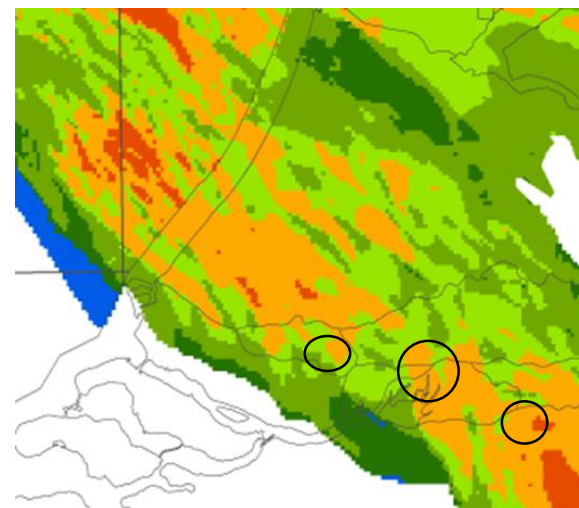
- › **Approach: comparing history and current conditions of CO2 reservoir with HC reservoirs**
 - › Tectonic & heat flow history
 - › Basin modeling_burial, temperature, HC generation & charge history
 - › Origin & dating CO2 charge
 - › Petrographic, mineralogical and geochemical study (optical microscopy, SEM, XRD, C, O, S isotopes); samples from 3 wells
 - › Relate burial, temperature & CO2 charge history with observed relative cementation history
 - › Determine major diagenetic processes/mechanisms
- › **Objectives**
 - › Understanding effects of CO2 on reservoir quality (with focus on cementation)
 - › Identification of good reservoir quality sweet spots

- › Studied reservoir:
 - › Upper Triassic Röt Fringe Sst (~245 Ma)
 - › Aeolian, fluvial & lacustrine
 - › Epicontinental setting
- › West Netherlands Basin/Roer Valley Graben:
Inverted rift basins



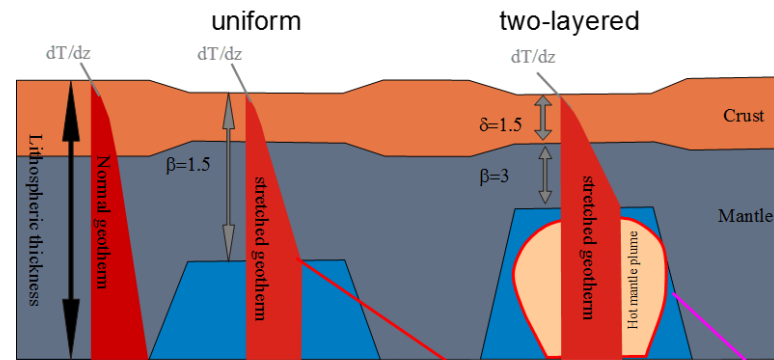
- › West Netherlands Basin/Roer Valley Graben: Inverted rift basins
 - › Jurassic-Early Cretaceous rifting
 - › Late Cretaceous & Paleogene inversion
 - › Gas-prone source rocks: Carboniferous coals and OM-rich shales
 - › Main phase of gas generation from Carboniferous sources: prior to Late Cretaceous inversion
 - › Kimmerian rifting: gas trapping structures

Simulated present-day
maturity at top Carboniferous

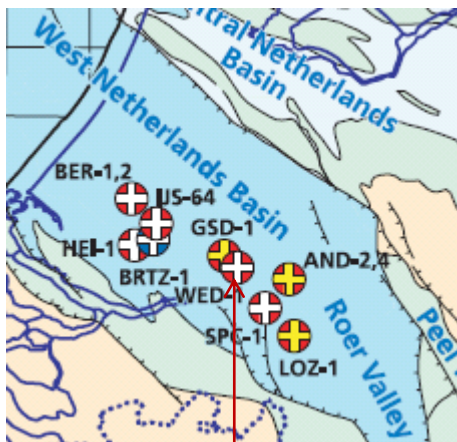


TECTONIC SUBSIDENCE AND HEAT FLOW

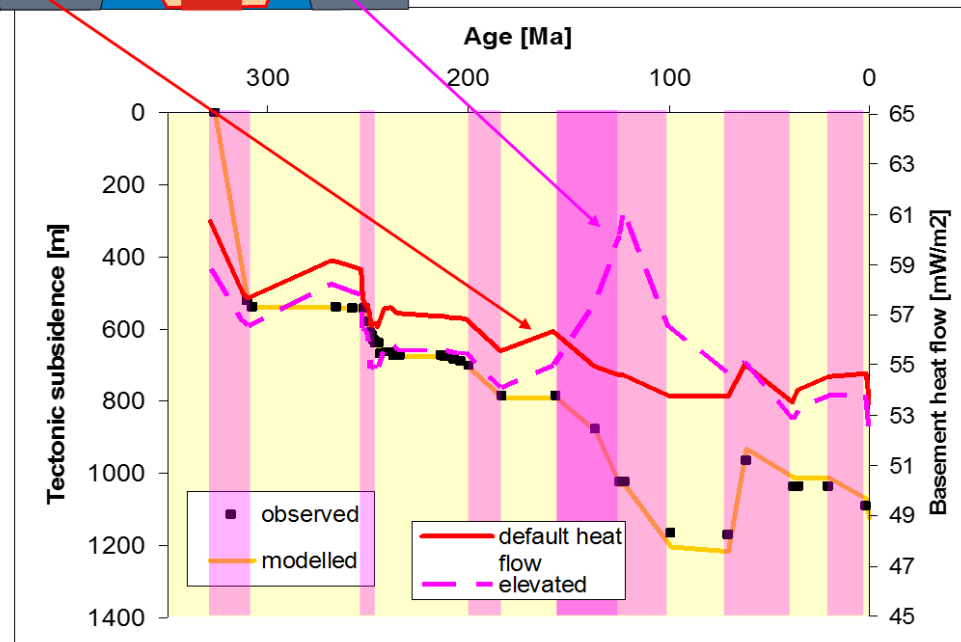
- › Late Jurassic-Early Cretaceous rift related elevated basal heat flow



- › Rift-related igneous activity

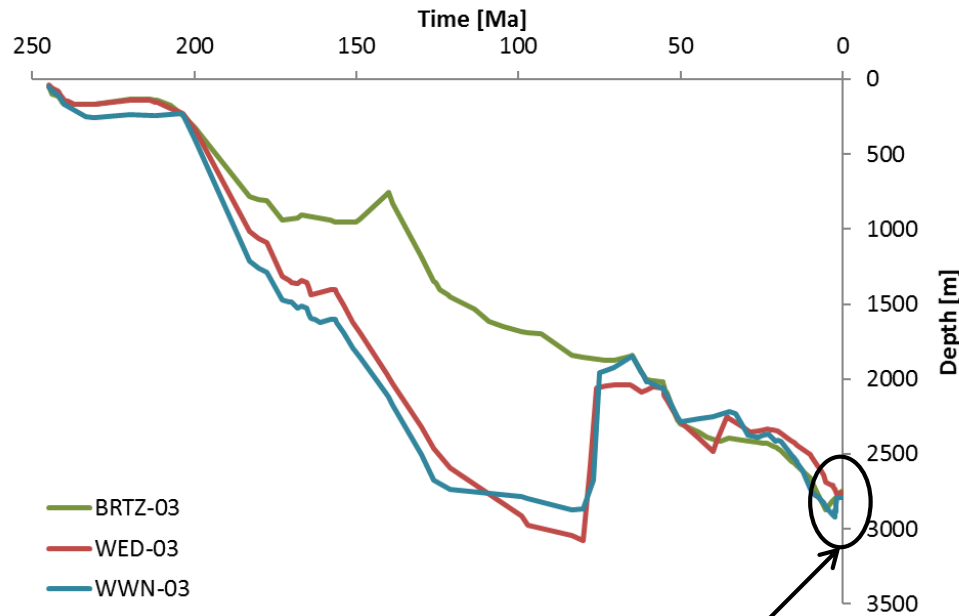


Age igneous rocks:
AND-02: 133 ± 2 Ma
LOZ-01: 132 ± 3 Ma
GSD-01: 125 ± 25 Ma

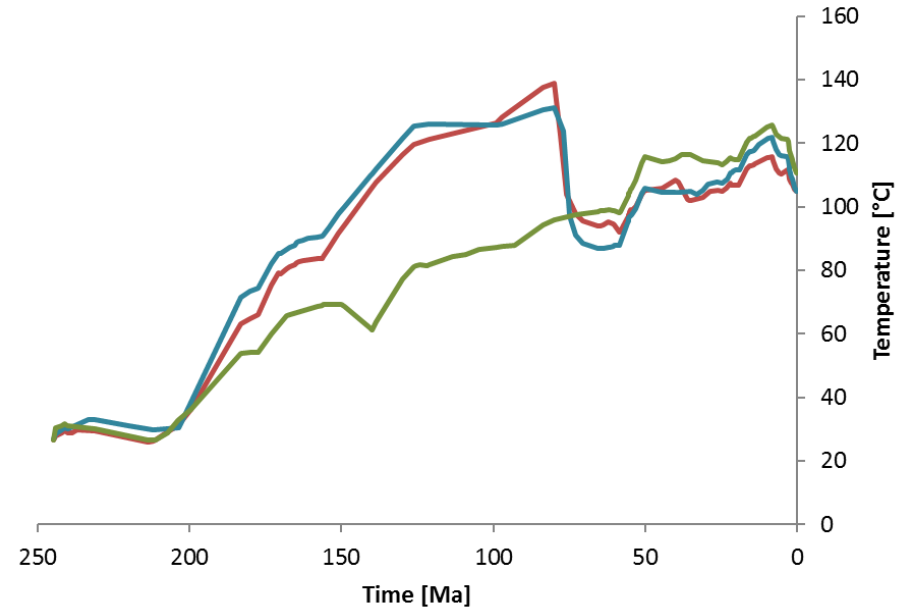


(From Van Wees et al., 2008)

BURIAL & TEMPERATURE HISTORY



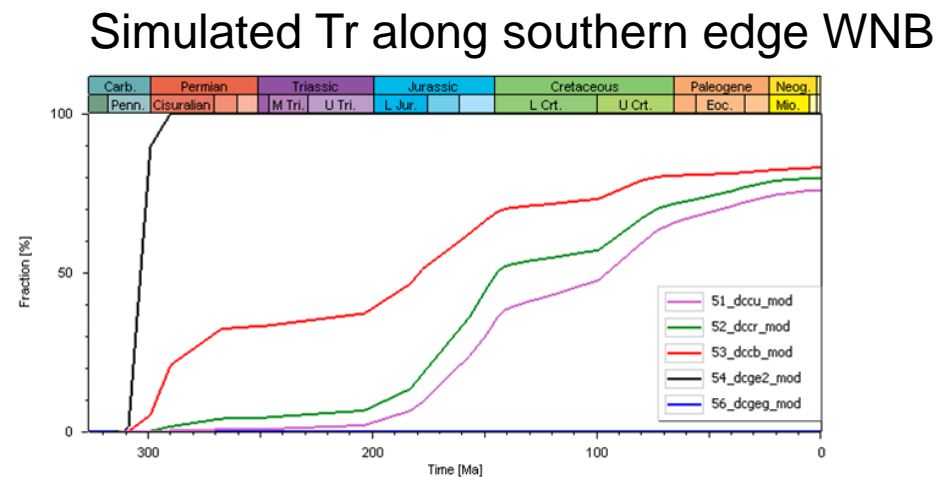
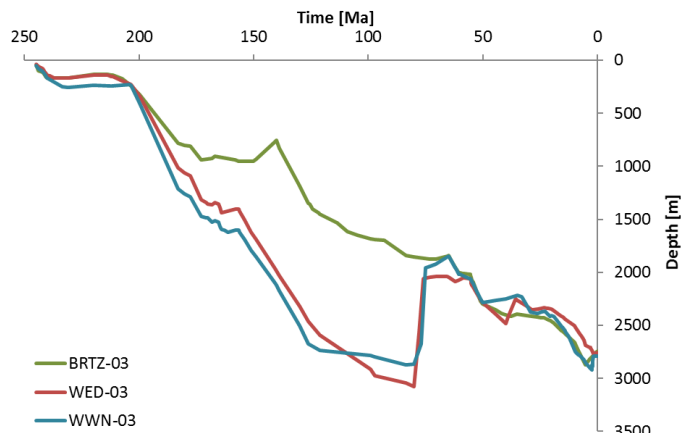
- › **WED**, **WWN** and **BRTZ** at same burial depth & T today
- › **BRTZ**
 - › Gradual continuous subsidence
 - › No inversion
 - › At max burial depth today



- › **WED**, **WWN**:
 - › Continuous subsidence until Late Cretaceous to 2800-3000m
 - › Major uplift during Late Cretaceous inversion
 - › Max burial and T prior to inversion

BURIAL AND MATURITY HISTORY

- › For all 3 well locations:
 - › Main phase of gas generation from Carboniferous sources: prior to Late Cretaceous inversion
 - › At southern edge basin (BRTZ)
 - › Gas generation continuous until present-day



- › Carbon stable isotopes ($\delta^{13}\text{C}$) of CO_2 can be of help to identify the possible sources of CO_2
- › The ratio difference (δ) between ^{13}C and ^{12}C in parts per thousand (‰), relative to standard:

$$\delta^{13}\text{C} = \left[\left\{ \frac{(^{13}\text{C}/^{12}\text{C})_{\text{sample}}}{(^{13}\text{C}/^{12}\text{C})_{\text{standard}}} \right\} - 1 \right] * 1000$$

- › The ratio of ^{13}C to ^{12}C is conventionally compared to the standard 'Peedee Formation Belemnite' and the result is given in a per mil quantity ($\delta^{13}\text{C}$ ‰ PDB).

- › **Werkendam CO₂-rich field**

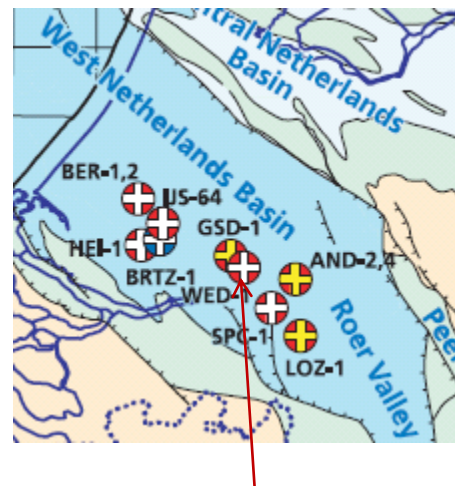
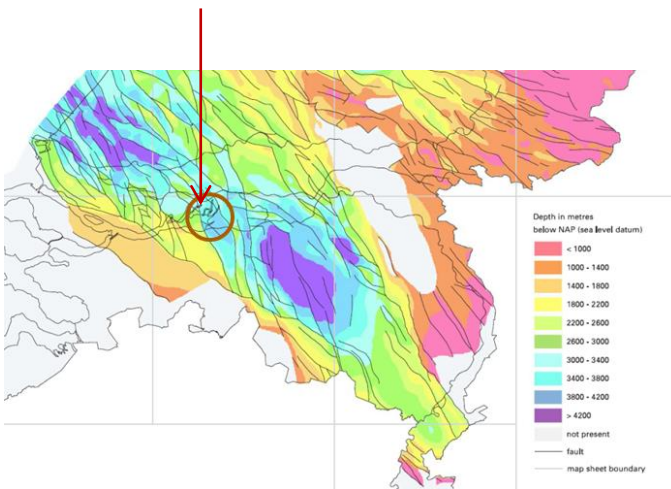
- › **WED-03: $\delta^{13}\text{C}_{\text{CO}_2} = -4.4\text{‰ PDB}$**

- › In general: magmatic/volcanic degassing as CO₂ source corresponds to:
 - › **$\delta^{13}\text{C}_{\text{CO}_2} : -7 \text{ to } -4 \text{‰ PDB}$** (Wycherley et al., 1999)
 - › More depleted values of $\delta^{13}\text{C}_{\text{CO}_2} \text{‰}$ occur at increasing distance from volcanic/magmatic source (e.g. Brauer et al., 2013; Hoefs, 2015), because of
 - › Fractionation (good solubility CO₂; HCO₃⁻ formation)
 - › Mixing with CO₂ derived from other sources
 - › CO₂-rock interaction

ORIGIN AND TIMING CO₂ CHARGE

› Werkendam CO₂ rich field

- › WED-03: $\delta^{13}\text{C}_{\text{CO}_2} = -4.4\text{‰}$
 - › Magmatic origin
 - › Alternative possibility origin: thermal metamorphism carbonates
- › Extensive Late Jurassic-Early Cretaceous rifting related igneous activity
- › WED-01: cuts through 2 faults and intrusive
- › Reactivation faults during rifting & Late Cretaceous-Paleogene inversions



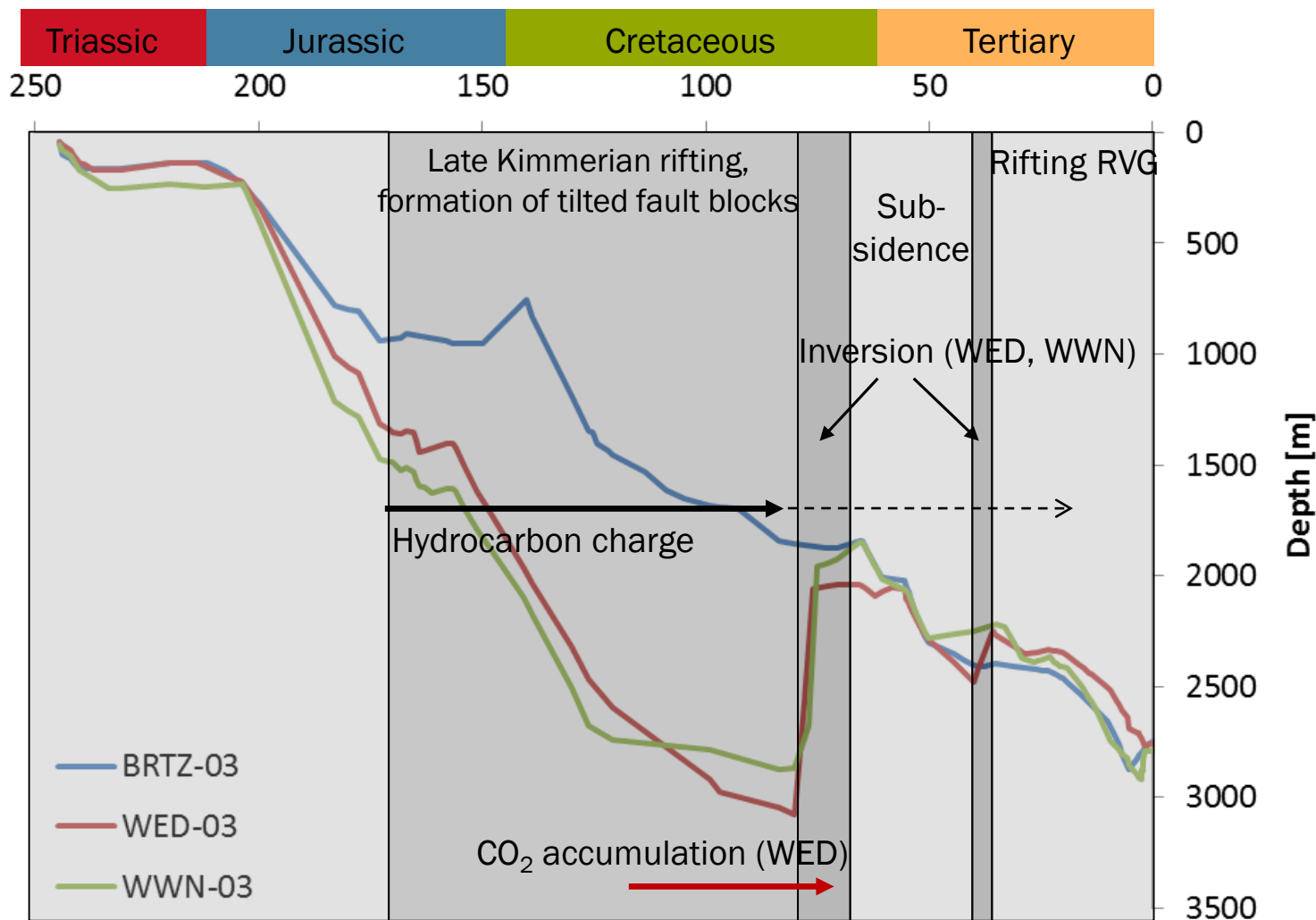
Early Cretaceous Age igneous rocks:

AND-02: $133 \pm 2 \text{ Ma}$

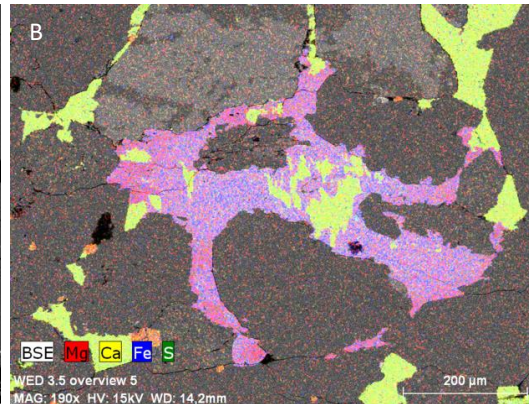
LOZ-01: $132 \pm 3 \text{ Ma}$

GSD-01: $125 \pm 25 \text{ Ma}$

BURIAL, T AND CHARGING HISTORY



Max Temperature due to burial ~140 oC

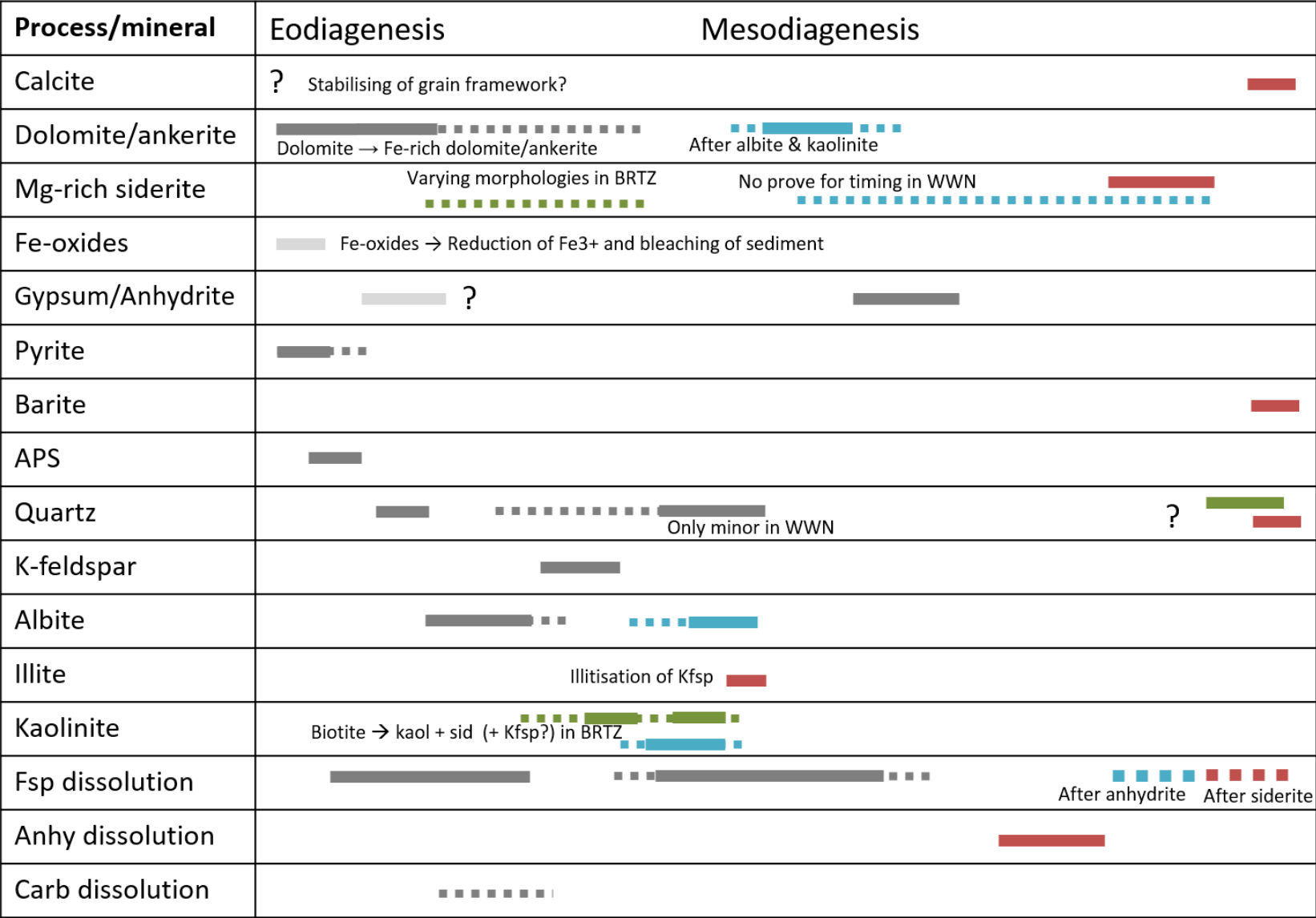


EDX element mapping (right)

Figure 1 is a color-coded map of the 1:250,000 scale geological map of the Kibabwa area. The map displays various mineralogical units, each represented by a specific color. A legend on the right side of the map lists the units and their corresponding colors:

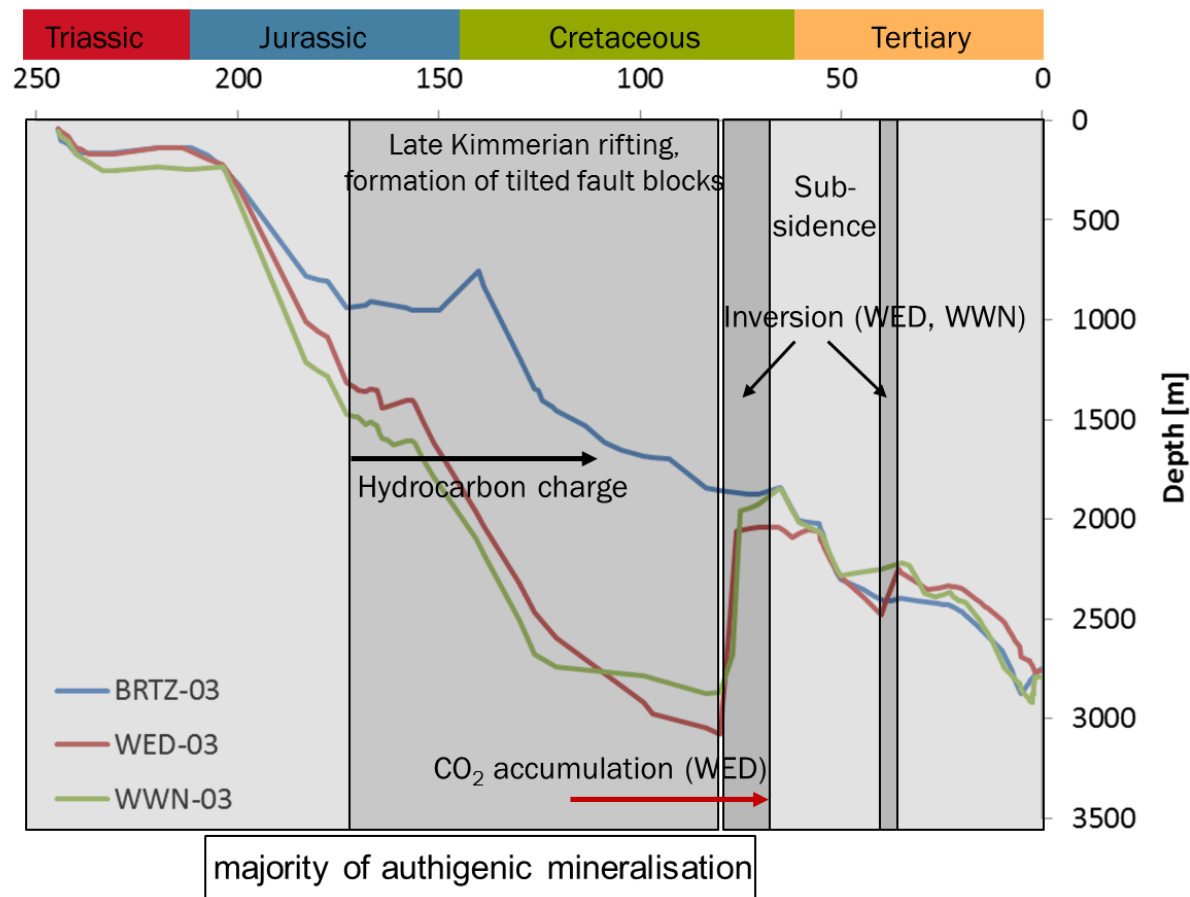
- Background (White)
- Quartz (Yellow)
- Silica (Light Green)
- K Feldspar (Blue)
- Plagioclase (Orange)
- Muscovite (Brown)
- Chlorite (Dark Green)
- Biotite (Red)
- Kaolinite (Light Blue)
- Ilite & illite-smectite (Dark Blue)
- Fe-illite & illite-smectite (Light Blue)
- Calcite (Cyan)
- Dolomite (Light Blue)
- Ferroan Dolomite (Dark Blue)
- Siderite (Dark Green)
- Pyrite (Yellow)
- Rutile & Ti Silicates (Red)
- Apatite (Pink)
- Tourmaline (Grey)
- Zircon (Pink)
- Ca Sulphate (Pink)
- Barite (Dark Grey)
- Halite (Light Grey)
- Undifferentiated (Dark Grey)

PARAGENETIC SEQUENCE

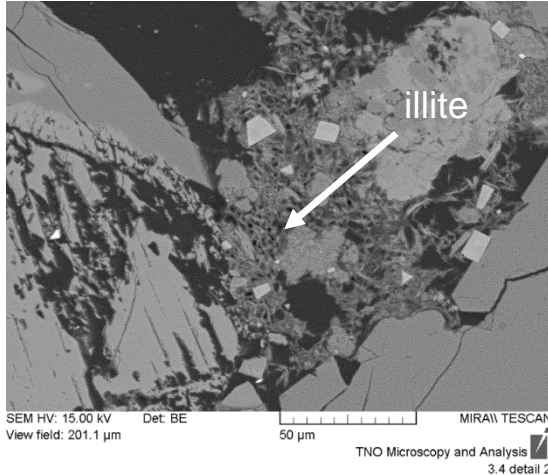


PETROGRAPHY: MAIN SIMILARITIES

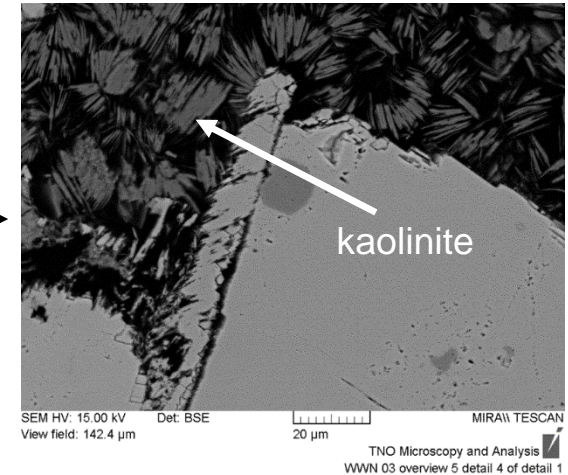
- › Observed mineral reactions and relative timing show similarities at the 3 locations in:
 - › Eodiagenesis (early diagenesis) and
 - › Early mesodiagenesis (burial diagenesis) phases



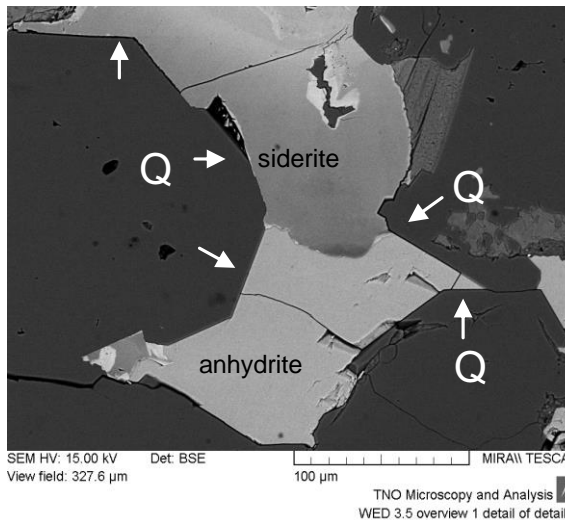
PETROGRAPHY: MAIN DIFFERENCES



Barendrecht + Waalwijk



Werkendam



› The following reactions are attributed to the presence of CO₂ in WED (Koenen et al., 2014):

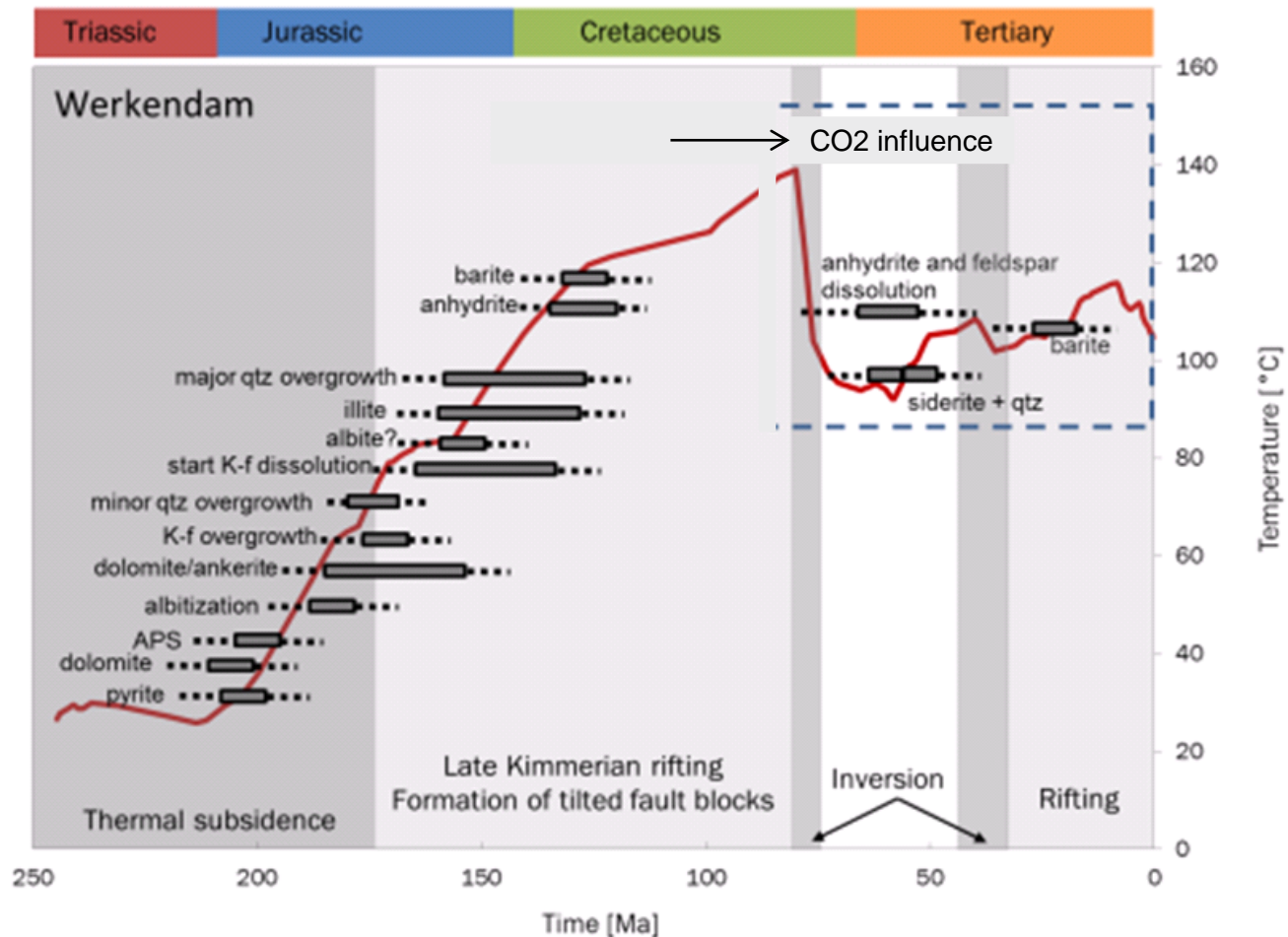
Dissolution of K-feldspar and anhydrite
Precipitation of Mg-rich siderite, barite and quartz

Lack of sources and sinks for several species suggest heterogeneity and/or transport

CO₂ charge created secondary porosity

INTEGRATION TEMPERATURE HISTORY, CO₂ EMPLACEMENT AND OBSERVED MINERAL REACTIONS

› **WED** natural analogue



- › Siderite in WED has trapped part of the CO₂ (Koenen et al., 2014)
- › Amount estimated based on average siderite content of 0.6-3.2 wt% in samples, density CO₂ = 420 kg/m³ (P= 210 bar, 120°C), porosity = 7.2%, and assuming no CO₂ has leaked from reservoir
- › Estimated amount of carbon trapping in siderite is 20-56% of the total CO₂

- › Knowledge on basin history is indispensable to study geochemical interaction between CO₂, formation water and reservoir rock on realistic geological timescales and therefore to predict cement assemblages and porosity development resulting from CO₂ sequestration
- › Early diagenetic mineral reactions are approximately similar for the 3 fields
- › Main part of paragenetic sequence occurred during burial diagenesis before influx of CO₂
- › Late stage mineral reactions in **WED**, are absent in **WWN** and **BRTZ**: these are interpreted to be induced by influx of CO₂
- › Differences in temperature history and CO₂ and CH₄ charge → differences in cement composition within a reservoir layer

- › Influence of CO₂: (additional) dissolution of anhydrite and K-feldspar & precipitation of Mg-rich siderite, quartz and barite
- › The **WED** sandstones are rich in siderite cement and illite
- › **BRTZ** and **WWN** sandstones are kaolinite-rich
- › **WED** has experienced late secondary porosity enhancement due to CO₂ charge
- › Estimated amount of carbon trapping in siderite in **WED** is 20-56% of the total CO₂

More detailed information: Koenen et al., Energy Procedia 37 (2013); Koenen et al., Energy Procedia 63 (2014)