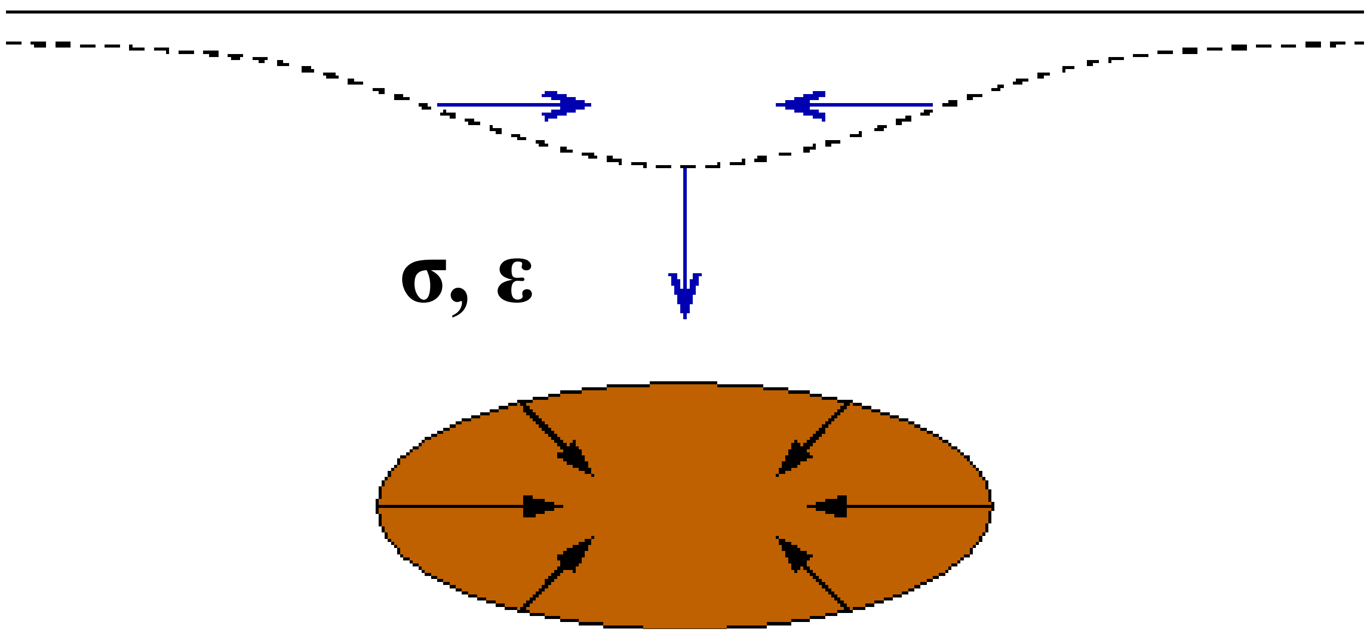
Anomalous Time Dependent Subsidence

by
Antony Mossop
NAM
Netherlands

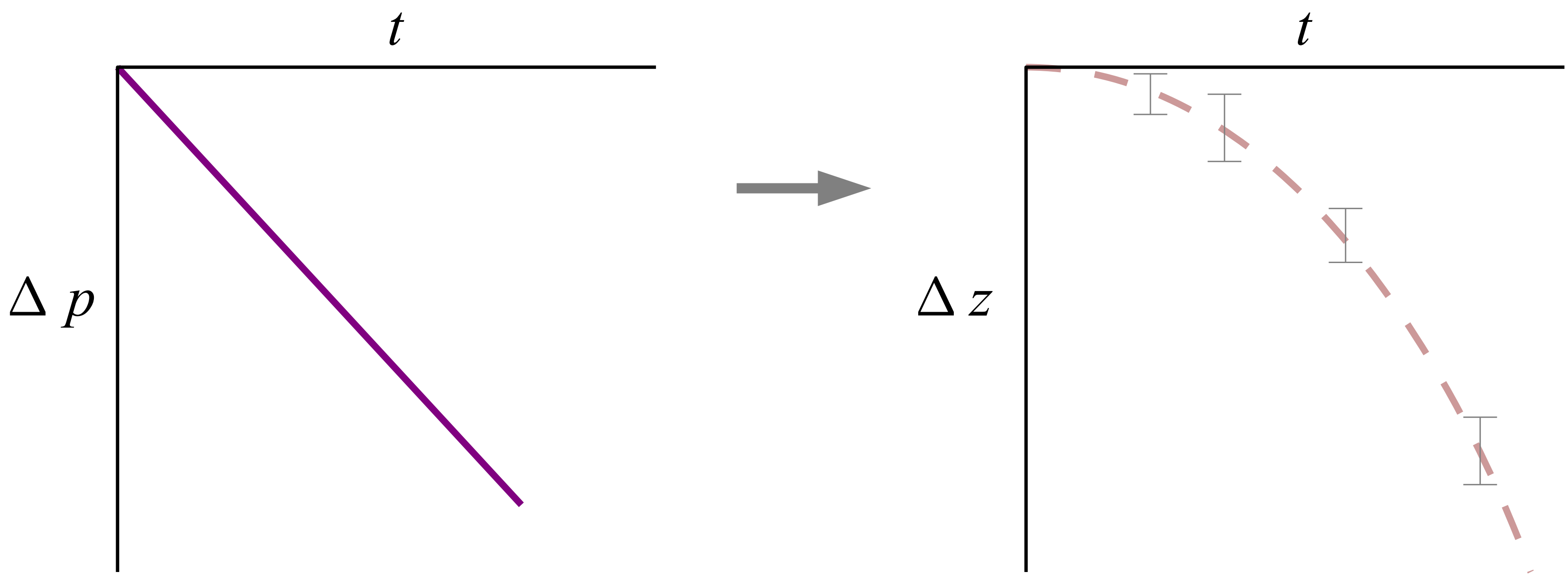
Statement of Purpose

The aim of this presentation is to inform stakeholders about the research program that NAM has put in place to investigate apparent anomalous time dependent subsidence in the Wadden gas fields. It has been presented to the steering committee facilitated by the KNAW Waddenacademie.

Even ignoring inertial effects (i.e. wave equation terms), the time taken for subsurface volume strain to induce surface deformation is still governed by acoustic velocity terms. But this is negligible.



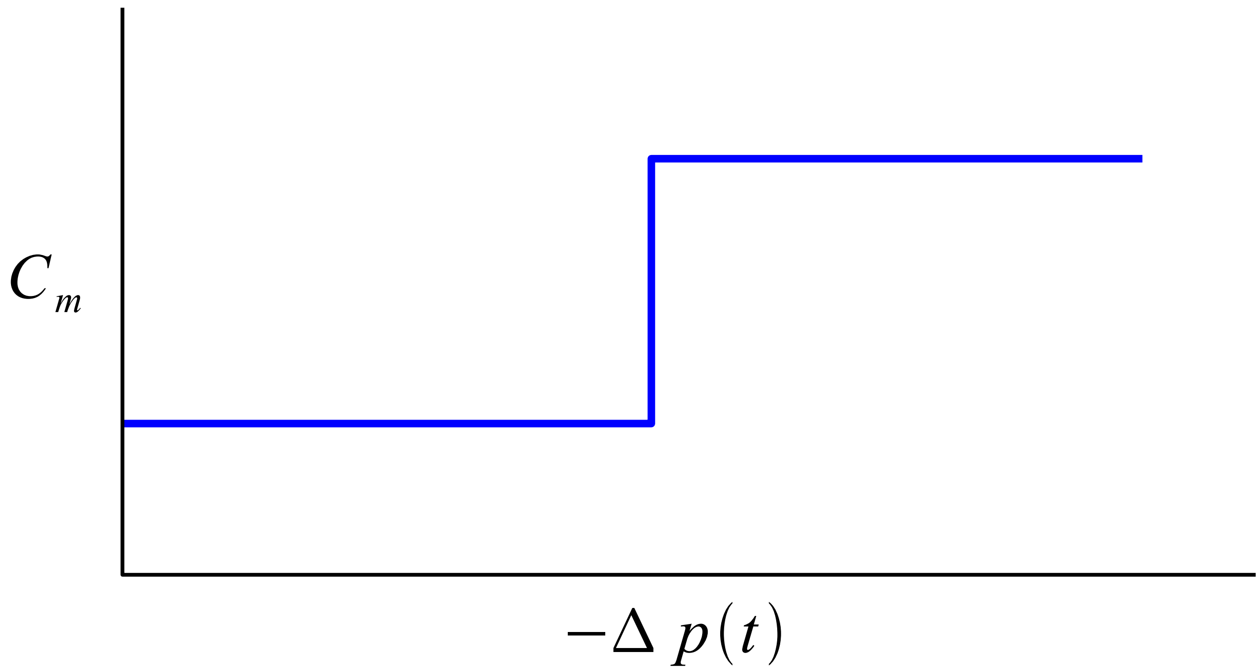
$$t \approx O\left[\frac{C_{ijkl}}{\rho}\right]$$



$$\Delta p(t) \propto \epsilon_{ii}(t) \propto \Delta z(t)$$

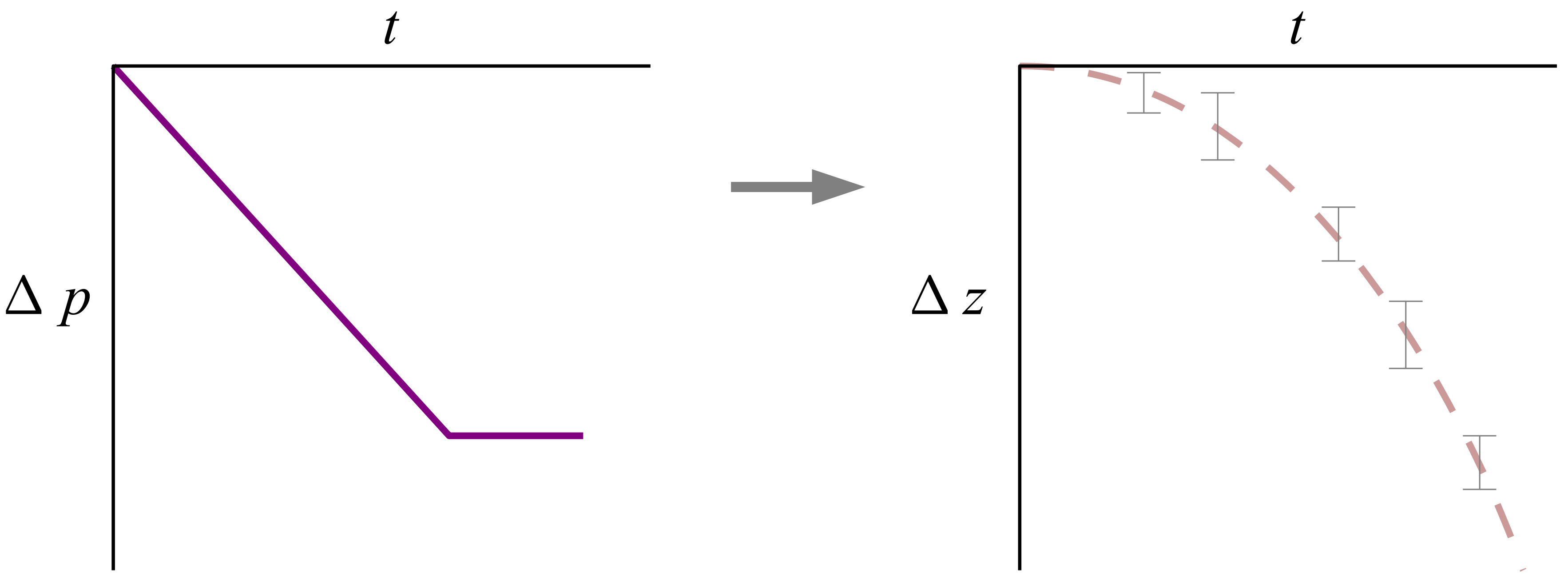
Apparent delayed subsidence, on the order of years, seems to be a relatively common phenomena (sampling and uncertainty issues notwithstanding). But where's the delay coming from?

Until recently we applied a 'bilinear' compaction model to try and explain this. It introduces two extra parameters, is physically plausible and satisfies the delayed subsidence observation (however, there is no evidence of this in laboratory tests...).

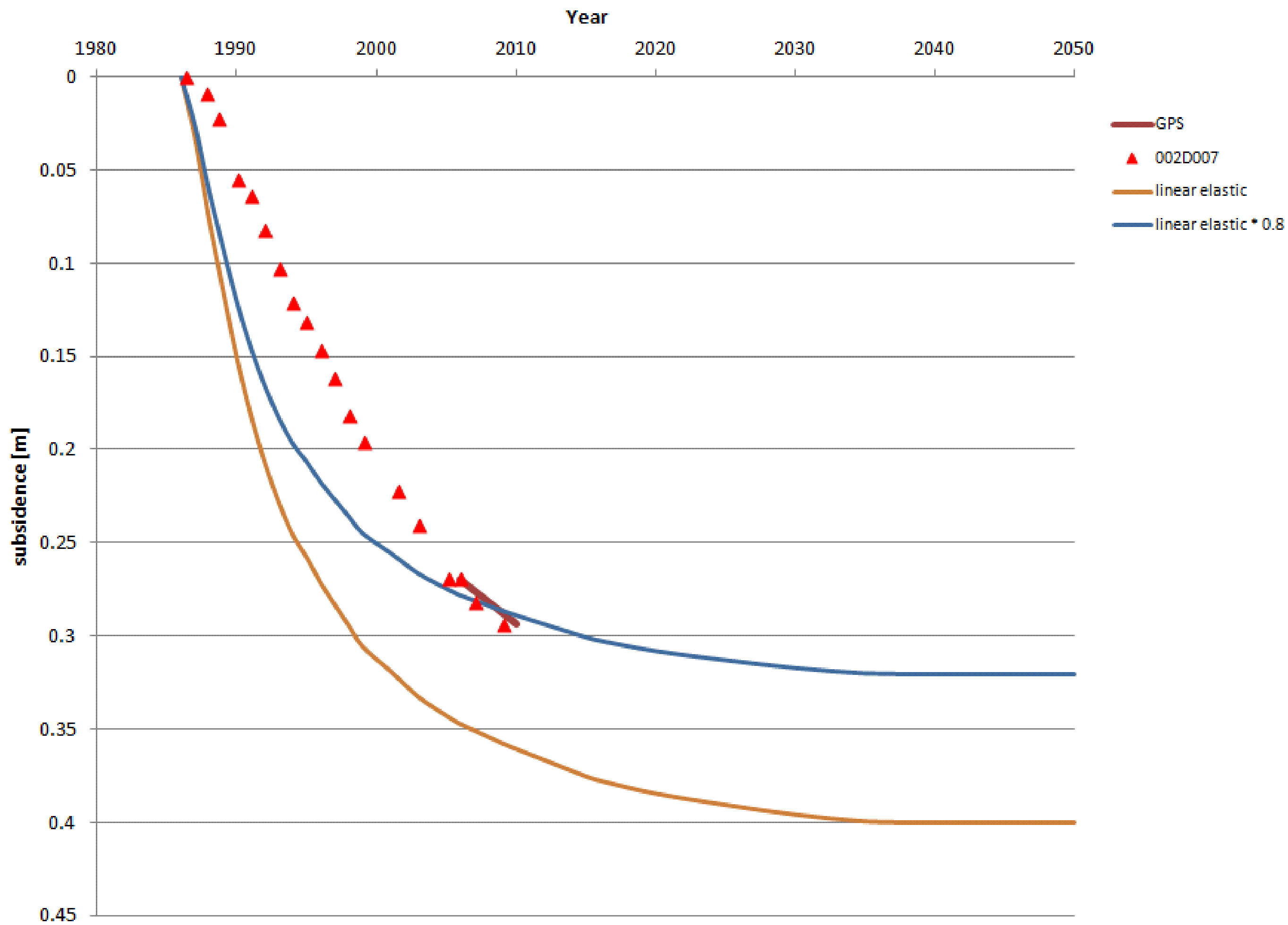


$$C_m \rightarrow C_m(\Delta p(t)) \rightarrow C_m(t)$$

Now though, there is mounting evidence that is beginning to suggest the following phenomenon is occurring (i.e. subsidence continuing after depletion has ceased)...

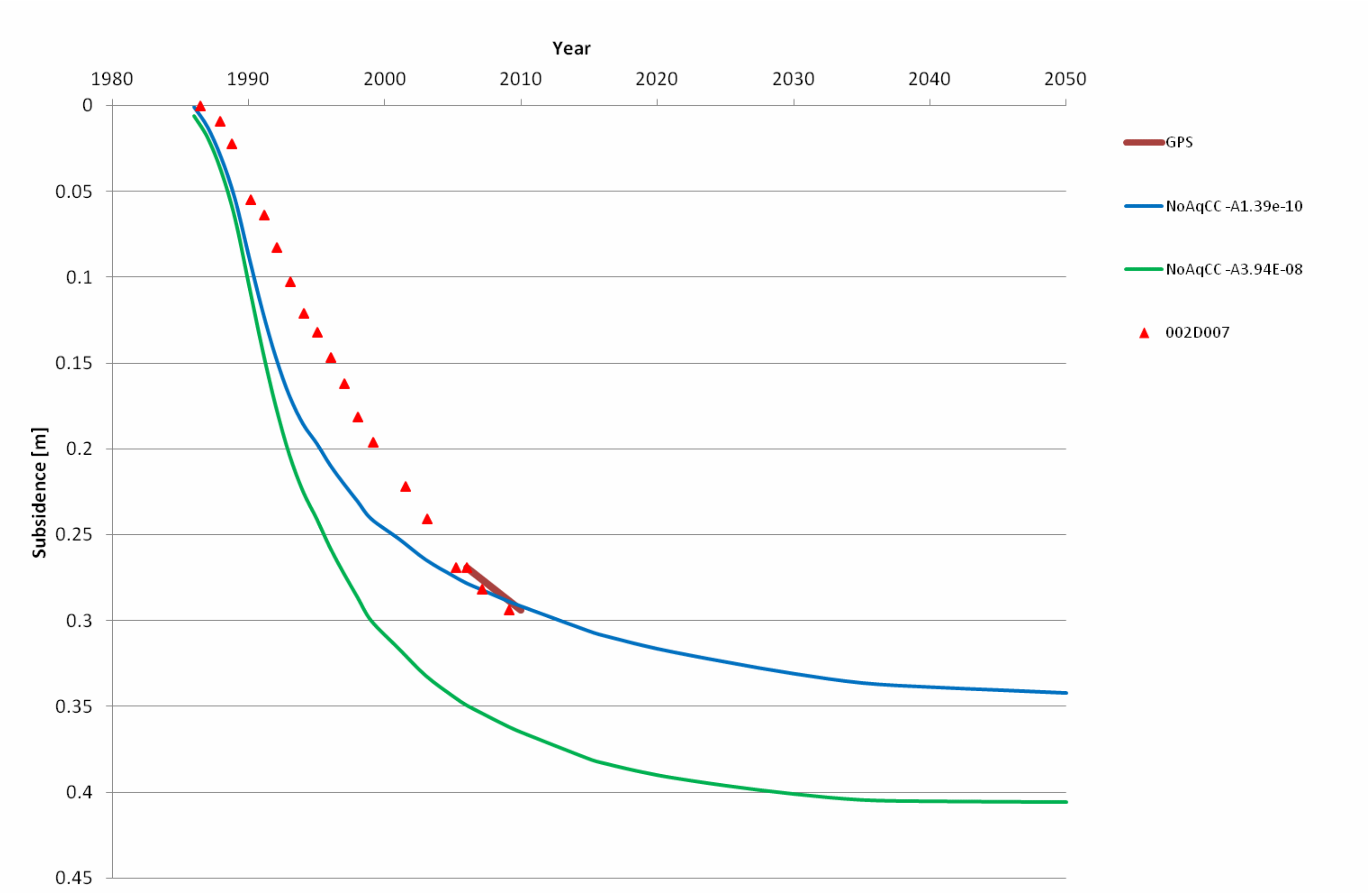


...and this cannot be explained by a bilinear compaction model.



Over the years there's been an increasing use of scaling parameters, calibration variables, etc... to 'improve fit'.

This is a best fitting structurally complex (FE) model with linear poroelasticity - it's got lots of parameters.



Best fitting structurally complex (FE) model with bi-linear poroelasticity and linear salt creep - even more parameters and it still doesn't fit...

“Numquam ponenda est pluralitas sine necessitate”
[“Plurality must never be posited without necessity”]

“Frustra fit per plura quod potest fieri per pauciora”
[“It is futile to do with more things that which can be done with fewer”]

Excessively complex models are affected by statistical noise (a problem also known as the bias-variance trade-off), whereas simpler models may capture the underlying structure better and may thus have better predictive performance.

The laboratory measurements show no sign of bilinear compaction behaviour. The scaling parameters have little support and the calibration factors are little more than 'fudge factors'.

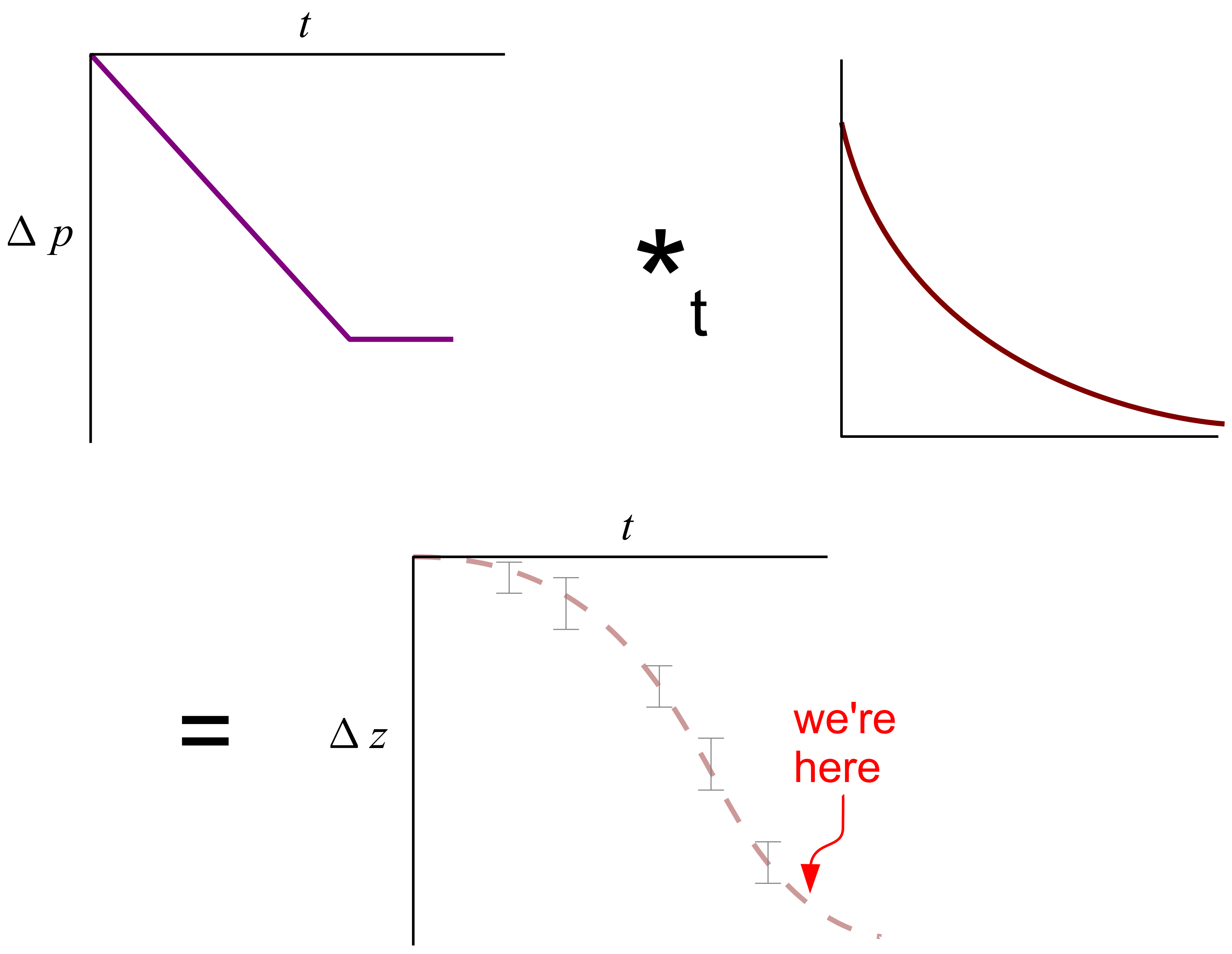
We lost predictive power by adding degrees of freedom in the attempt to fit the data.

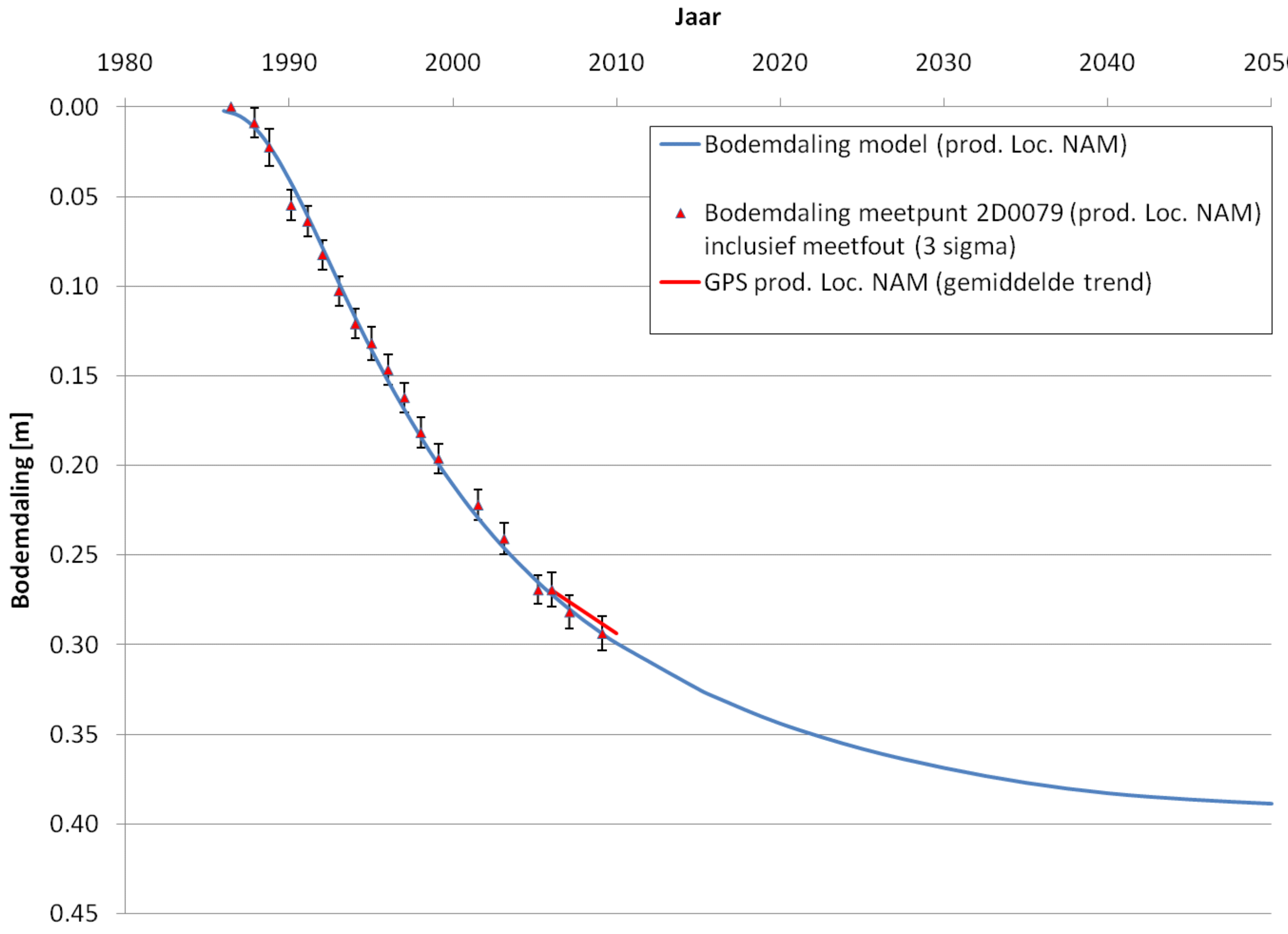
We needed to take a step back, take a look at the physics and only introduce parameters where absolutely needed and only when there's a clear physical reason.

One of the fundamental behaviours of dynamic systems, is that when you perturb them, they return to equilibrium via an asymptotic diffusive time decay (non-equilibrium dynamics).

It's the basic physics of the universe, and in general should always be a 'first assumption' where anomalous time dependence is observed in a perturbed system. The diffusion equation is simply the most basic (first order) description of non-equilibrium dynamics.

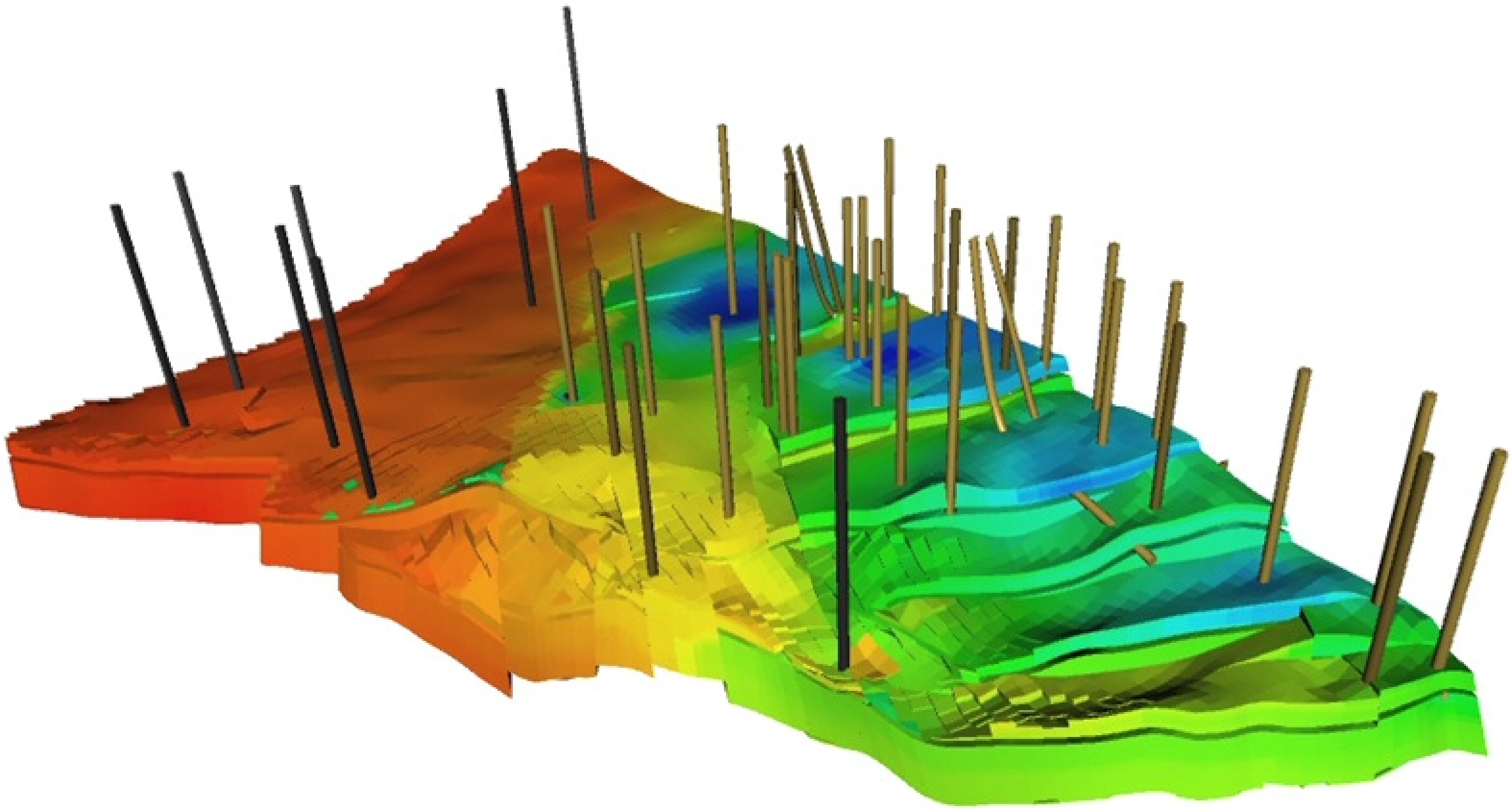
Anomalous Time Dependent Subsidence





A significant improvement in fit while using fewer parameters and compressibilities consistent with laboratory measurements (can even reduce structural complexity, salt creep, etc...).

However, there's more than one way to explain such decay phenomena. Perhaps the most obvious and likely, is that the effects of pressure diffusion are not properly captured in the reservoir and aquifer modeling.



There is also evidence of inelastic creep/damage type processes in unconsolidated and consolidated rocks that could also provide a possible explanatory mechanism.

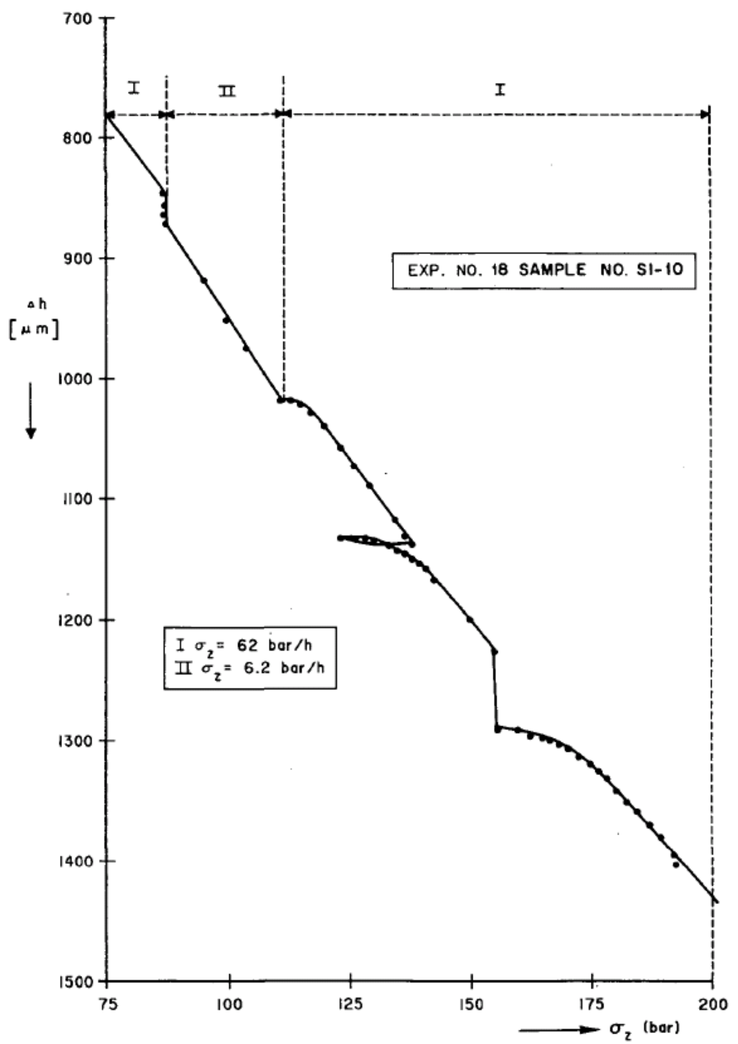


FIG.A9 COMPACTION BEHAVIOUR OF 170 μ SAND AFTER A CHANGE IN LOADING RATE, PARTIAL UNLOADING AND CREEP (OEDOMETER TEST)

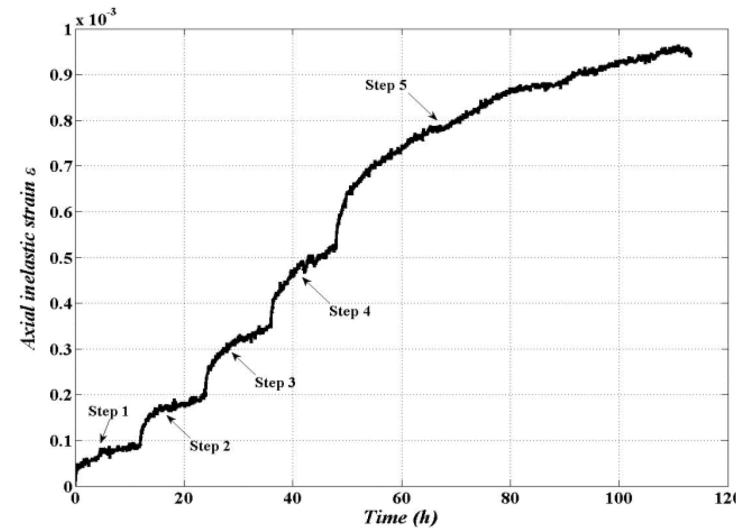


Figure 17. Creep strain vs. time (C9A)

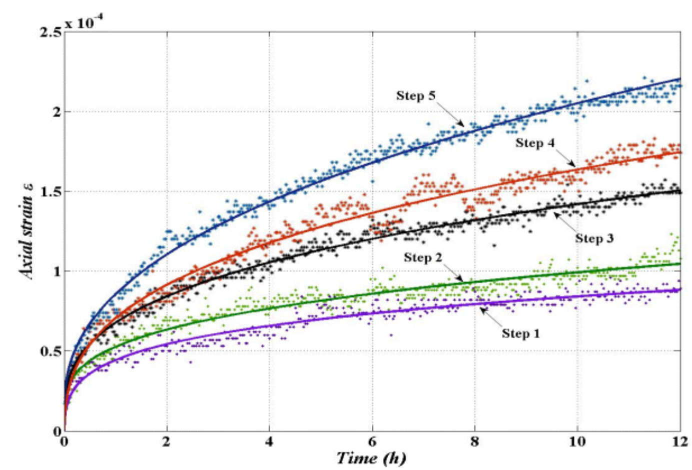
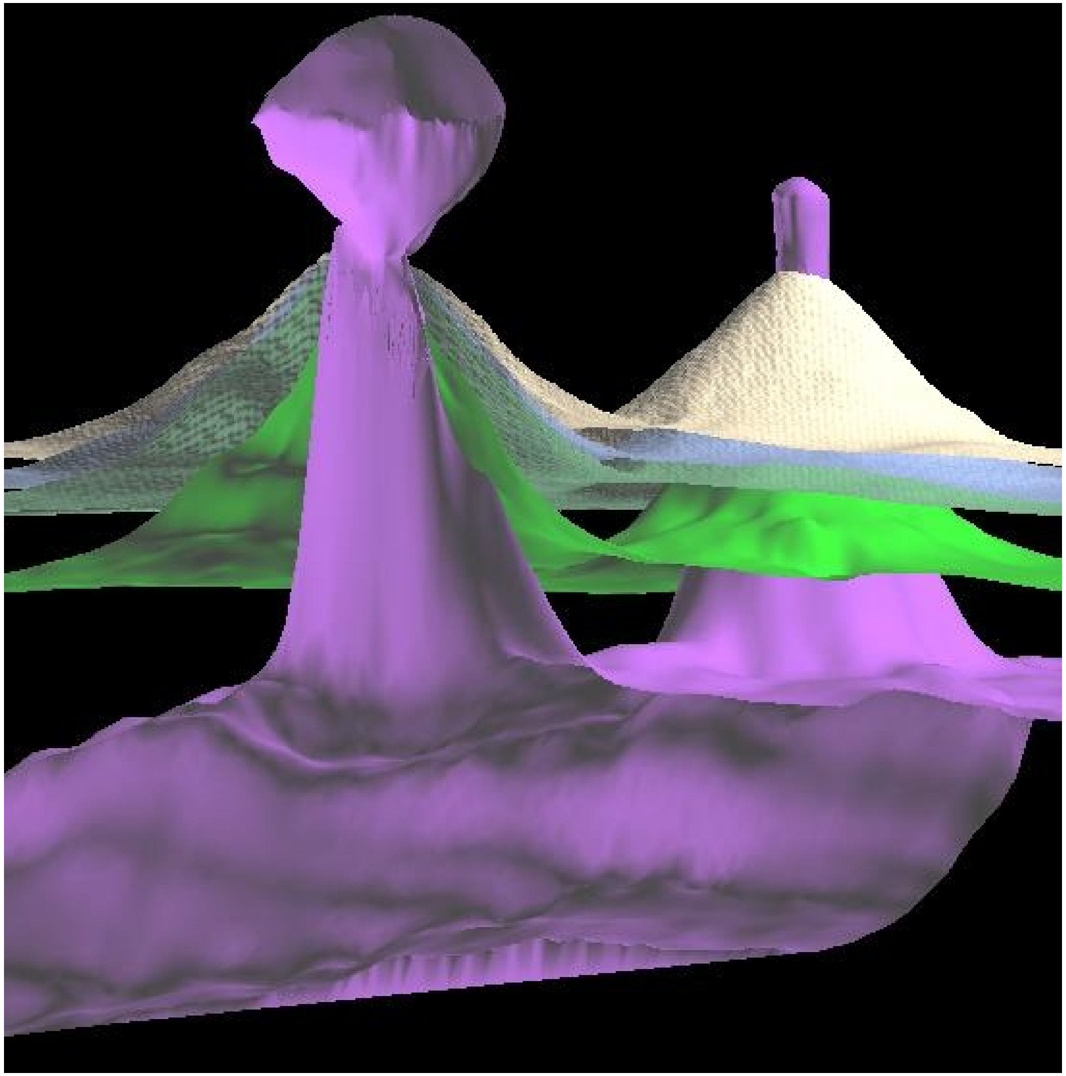
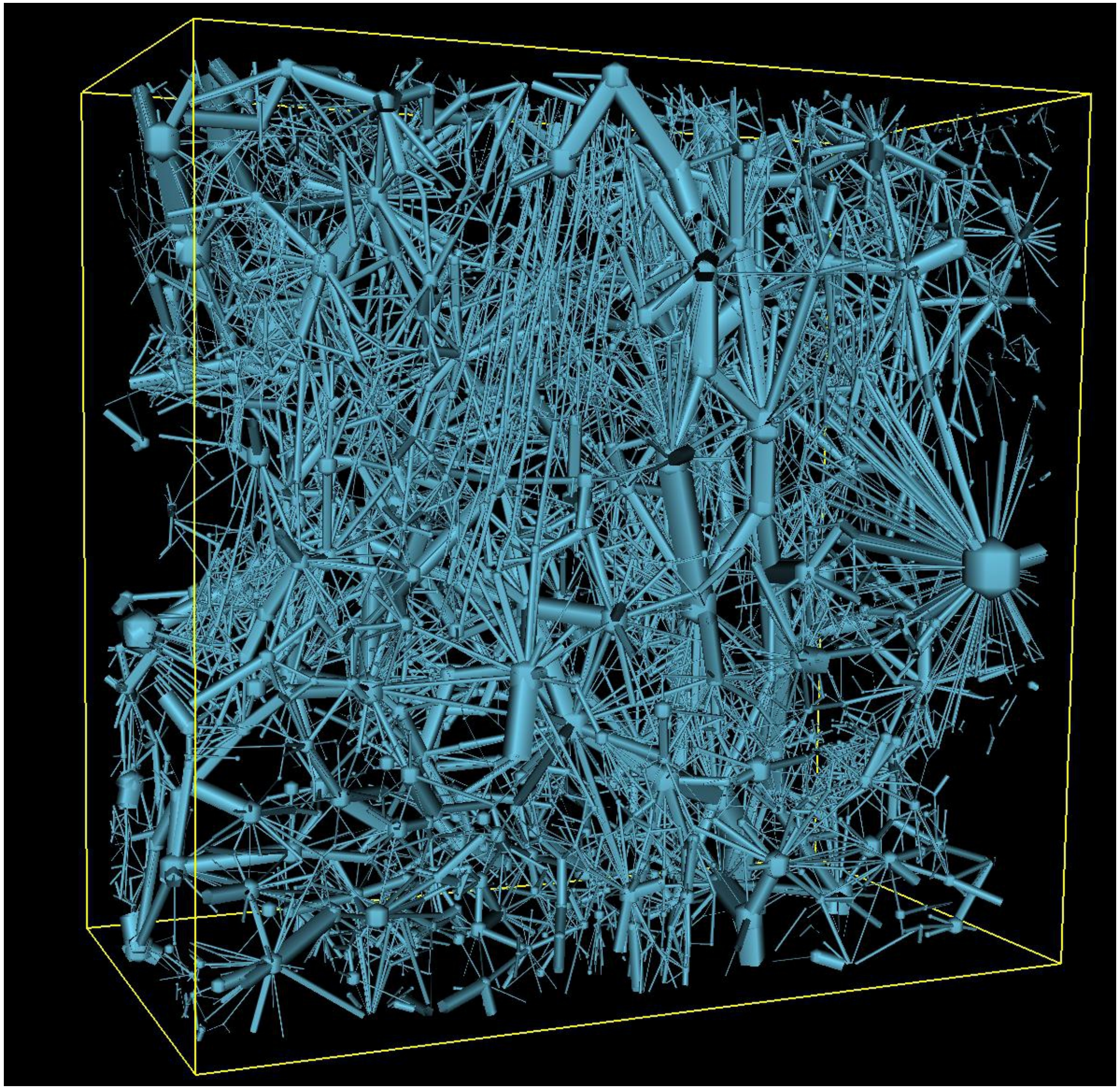


Figure 18. Profiles of creep strain within individual steps; the origin of coordinate is being translated (C9A)

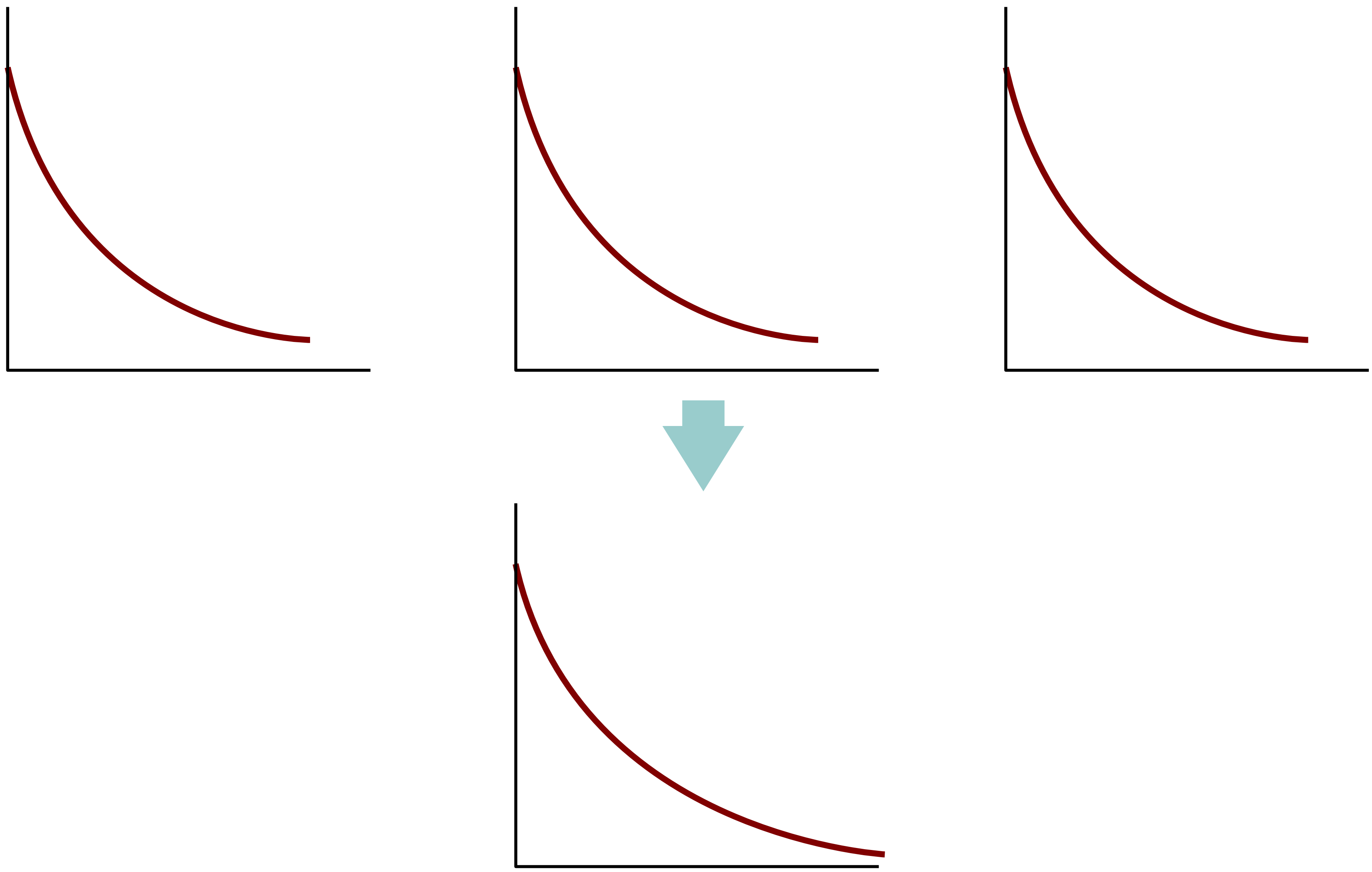
The visco-plastic creep properties of salt, combined with sparse geodetic survey data, can also offer a possible mechanism for explaining time dependency.



And a personal favourite of mine, is the time dependent compaction behaviour introduced by more realistic scale dependent pressure diffusion.



But an accumulation of decay type processes, just gives another decay process. It is not possible to uniquely identify the process just from the decay signature.



Research Program

The purpose of this research program is to provide an improved understanding of the production induced subsidence process, built from, and supported, by objective evidence and sound fundamental scientific principles. This then can provide the foundations of a subsidence modeling, monitoring and prediction strategy that provides clear and verifiable subsidence predictions within well defined uncertainty bounds.

Should deliver recommendations, practical advice and demonstrations (proof of concept) of an improved subsidence modeling, prediction and monitoring program.

Report to independent expert review panel

Report via peer reviewed open literature

Deadline of mid-2015

Candidate Hypotheses

Artifact of geodetic data

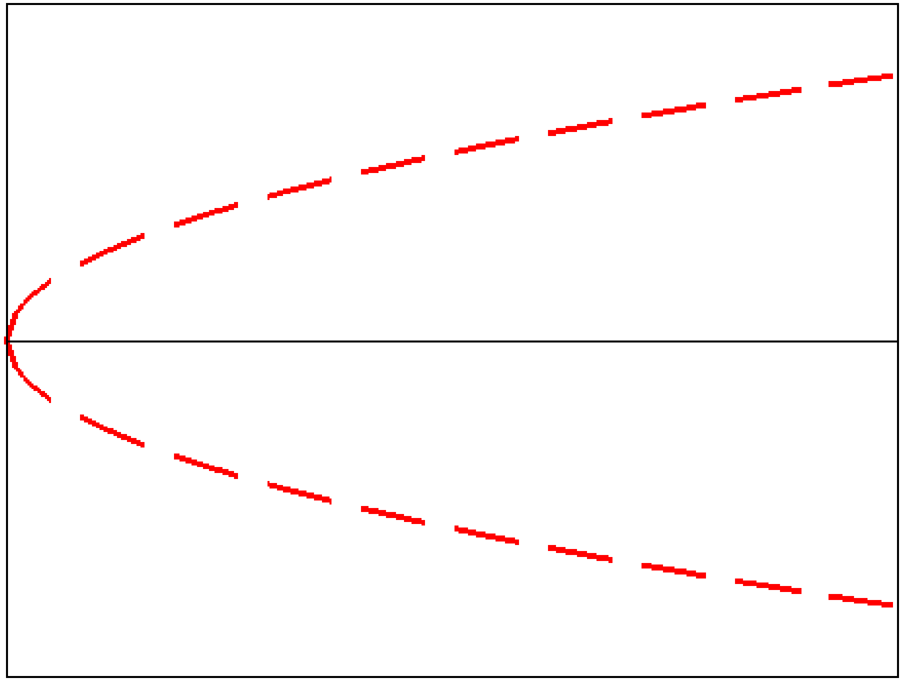
Artifact of geodetic data sparsity and salt flow

Inaccurate reservoir/aquifer modeling

Visco-plastic compaction of solid component

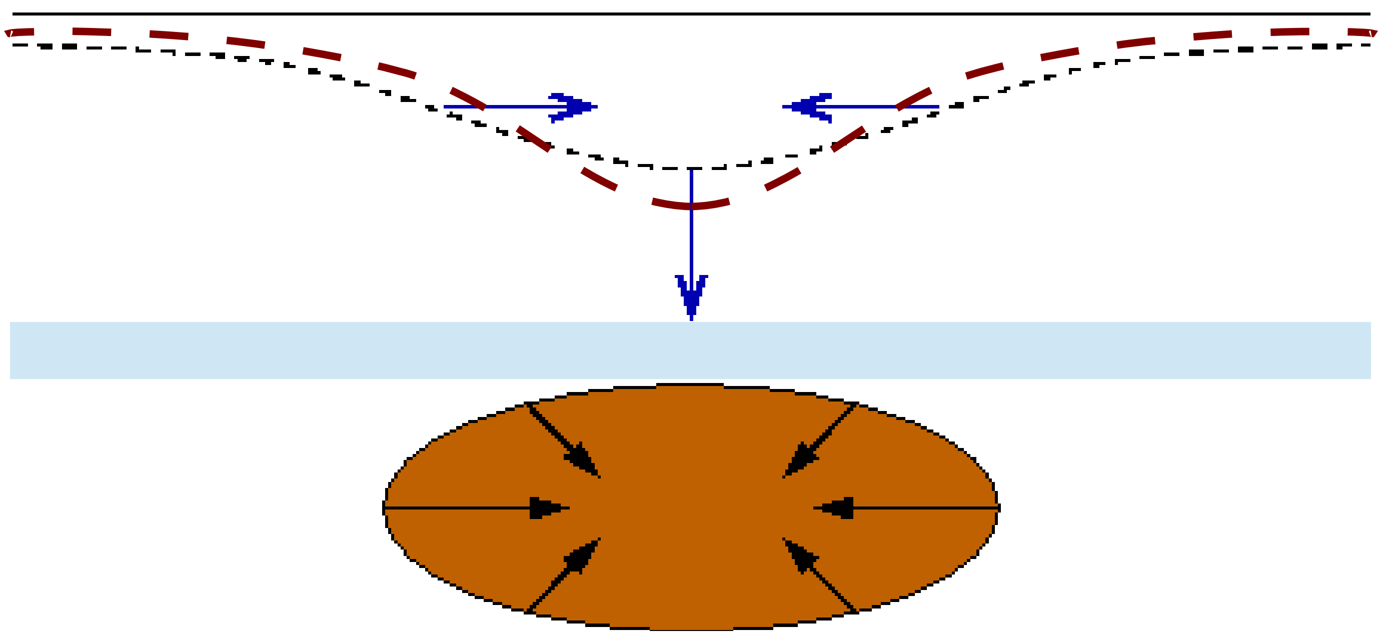
Pressure diffusion where permeability has 'long tail' statistical distribution

….?



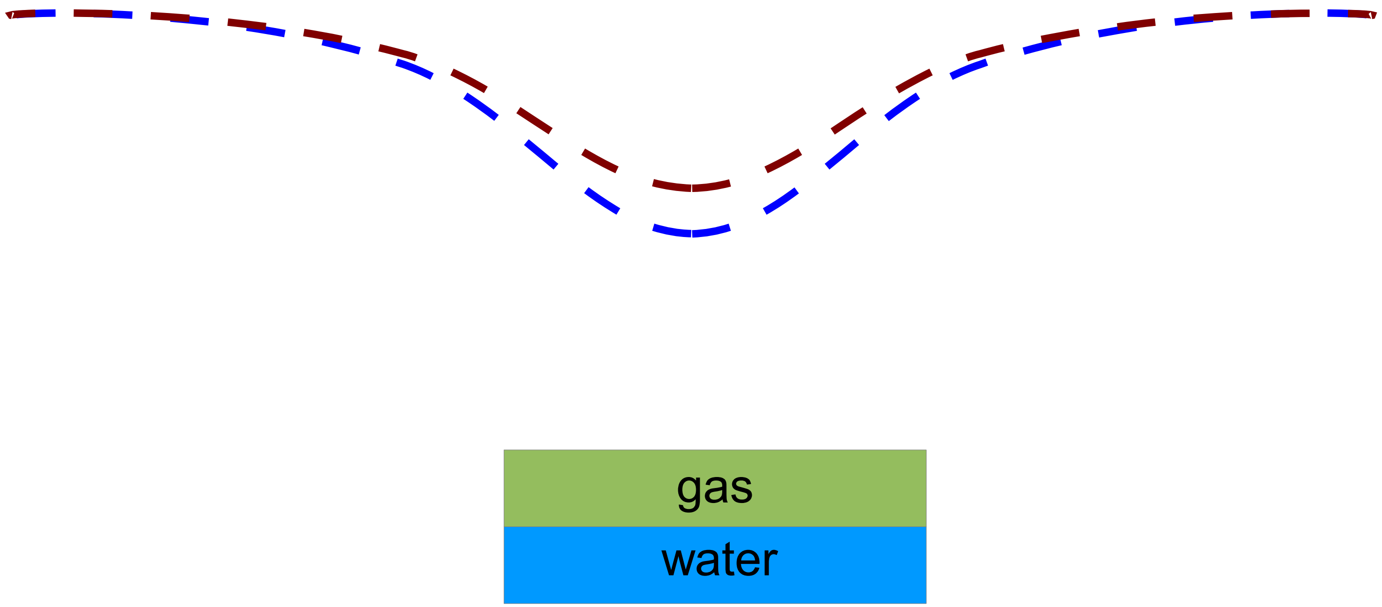
Artifact of geodetic data

Geodetic data known to have more complex spatial and temporal correlation and noise structure than is generally assumed, e.g. strong evidence that temporal error grows faster than random walk.



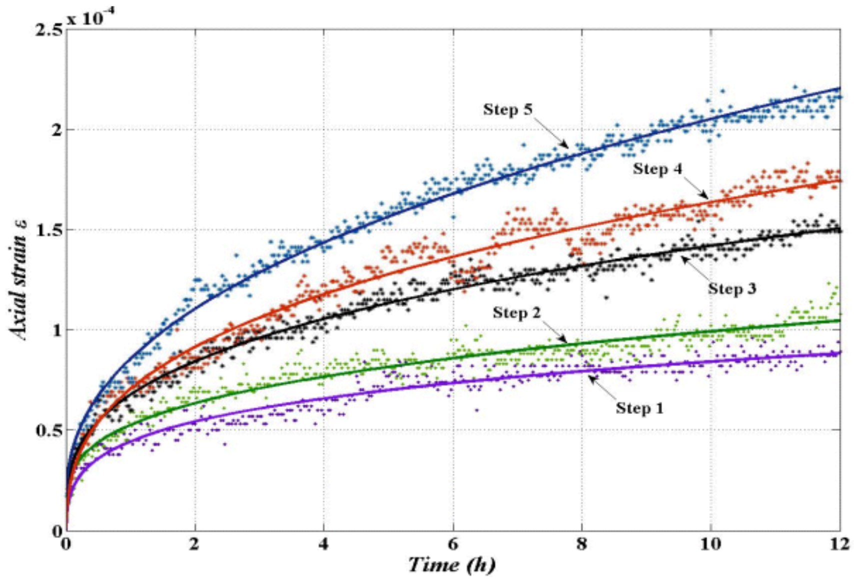
Artifact of geodetic data sparsity and salt flow

Salt flow known to cause deepening of subsidence in the centre (where geodetic SNR is high), and shallowing at the edges (where geodetic SNR is low).



Inaccurate reservoir/aquifer modeling

For example incorrectly modeled pressure diffusion into an aquifer could lead to increased total compaction with time.



Visco-plastic compaction of solid component

A visco-plastic (time dependent) volume strain process within the solid grain structure of the rock – creep at grain contacts, damage, etc. May be difficult to determine how to upscale such processes.

Pressure diffusion where permeability has 'long tail' statistical distribution

A 'long tailed' permeability distribution (commonly observed), produces a complex dendritic drainage pattern which would be consistent with a seemingly high connection permeability but low poroelastic compaction permeability.

Data Quality, Uncertainty and Statistics

Physical Models (Continuum Mechanics)

Subsidence Data

Constitutive Laws

Salt Mechanics

Validation and Testing

Data Quality, Uncertainty and Statistics

** Duration - 1 year*
** Time budget: geomechanics researcher - 0.5 year; + undefined input from others*

Improved clarity, rigour and sophistication concerning the sources, quantification and implications of uncertainty and error in the data, needs to be adopted. This information is just as important to the modeling and prediction process as the data themselves. This is central to the testing of hypotheses and the formulation of decisions and conclusions.

Physical Models (Continuum Mechanics)

** Duration - 3 years*
** Time budget: geomechanics researcher - 1 year; + undefined input from others*

The theoretical models themselves need to be reviewed. These are often applied unquestioningly, and implicitly taken as exact. Yet in reality they are idealisations based on simplifications and assumptions that are clearly violated by the real systems under consideration.

Subsidence Data

** Duration - 2 years*
** Time budget: geomechanics researcher – 0.5 year; + undefined input from geodesy/geomatics*

The poor spatial and temporal sampling of surface deformation surveys are a major impediment to investigating second order behaviour. This can be greatly improved using presently available InSar techniques and there are continuous developments in this discipline. Proper and careful integration of these more advanced and higher resolution geodetic data into the subsidence modeling process must also be stepped up in priority.

Constitutive Laws

** Duration - 3 years*
** Time budget: geomechanics researcher – 0.5 year; + 0.5 year rock mechanics personnel*

The constitutive laws and their parameters, governing the deformation of the materials involved, need to be reviewed. Much of what is available is based on fitting noisy and somewhat inadequate laboratory measurements to idealised curves. While adequate for first order modeling exercises, this is potentially limiting if greater accuracy is needed. The regulatory authorities have been consistent in questioning the validity of the constitutive laws presently used over times scales of tens of years. This will be difficult to address within the time span of this project.

Salt Mechanics

** Duration - 3 years*
** Time budget: geomechanics researcher - 0.25 year + JIP partners*

Universiteit Utrecht

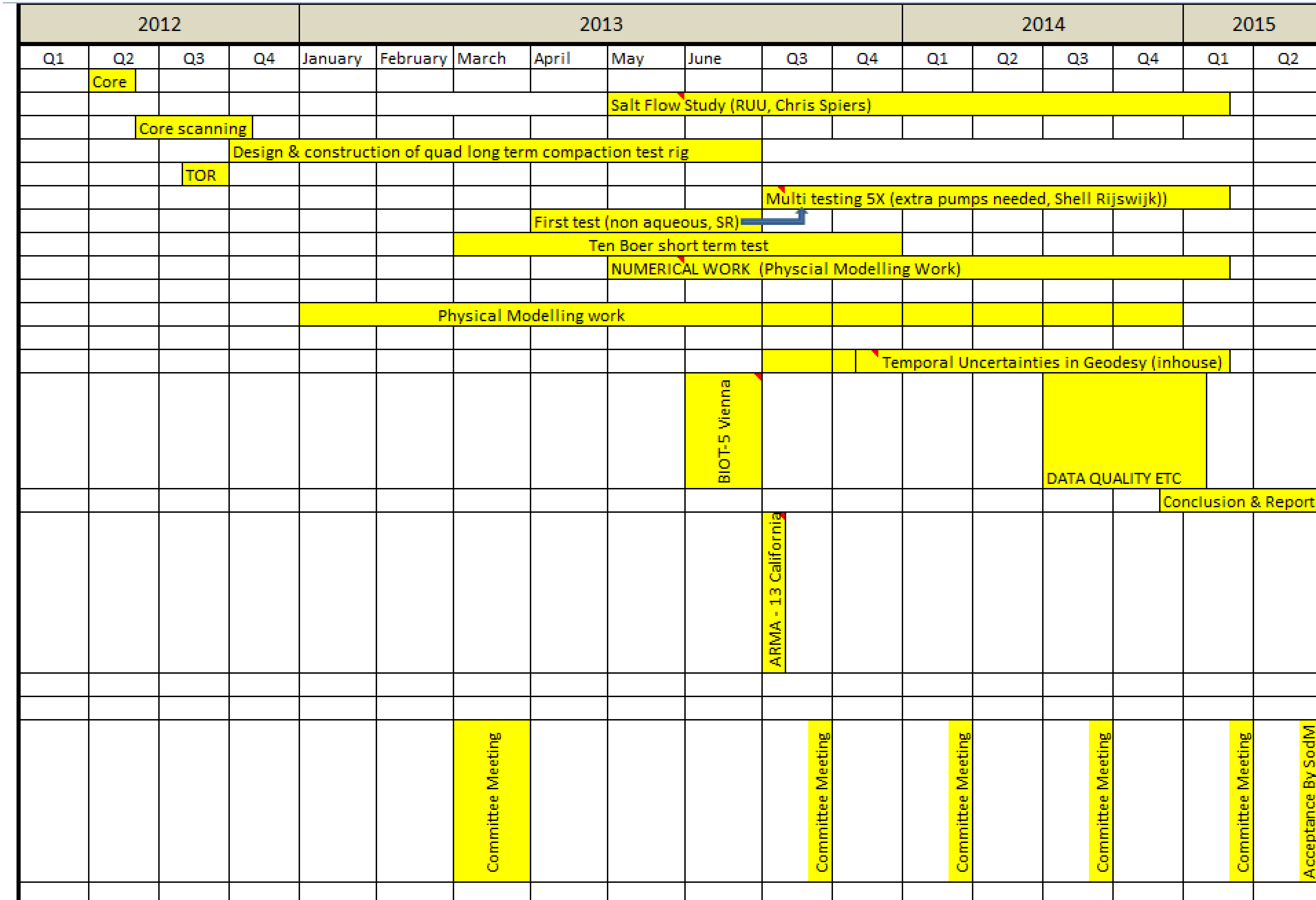
Agreement to fund a research student (post-doc) to investigate the limits as to whether apparent anomalous time dependent subsidence could be simply an artifact of salt creep flow, and sparse spatial and temporal sampling. Prof. Chris Spiers is coordinating and act as principal investigator. Proposal received Q1 2013

Validation and Testing

** Duration - 3 years*
** Time budget: geomechanics researcher – 0.5 year; + 0.5 undefined input from others*

With respect to the computation of predicted subsidence, there is a clear need to identify and, where possible, eliminate, unrealistic assumptions and approximations implicit in the fundamental physical models. This involves going beyond simply determining the impact such simplifications have on prediction capabilities, mentioned earlier as a necessary first step, but investigating how to improve the modeling effort. This will almost certainly involve higher order physical models and potentially an increasing reliance on semi-analytic or numerical solutions. These need to be very cautiously applied.

Timeline


2012
2013
2014
2015
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Q2
Q3
Q4
January
February
March
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June
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Q1
Q2
Core
Salt Flow Study (RUU, Chris Spiers)
Core scanning
Design & construction of quad long term compaction test rig
TOR
Multi testing 5X (extra pumps needed, Shell Rijswijk))
First test (non aqueous, SR)
Ten Boer short term test
NUMERICAL WORK (Physcial Modelling Work)
Physical Modelling work
Temporal Uncertainties in Geodesy (inhouse)
BIOT-5 Vienna
DATA QUALITY ETC
Conclusion & Reportin
ARMA - 13 California
Committee Meeting
Committee Meeting
Committee Meeting
Committee Meeting
Committee Meeting
Acceptance By SodM

Questions