







# CRUSDe: A PLUG-IN BASED SIMULATION FRAMEWORK FOR COMPOSABLE CRUSTAL DEFORMATION SIMULATIONS

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## Abstract

Within geoscience unit impulse responses in the form of Green's function are often used to analyze the dynamics of the Earth's crust in response to changes of surface loads. A generalized formulation of this method was derived and implemented in the simulation framework CrusDe (C/C++ languages). The information flow between model elements such as Green's function, load or relaxation function is realized in a way that enables free composition of these elements when a specific deformation problem is approached. CrusDe allows for the exchange of particular model element implementations through an architecture that defines interfaces for generic communication between the simulation core and the model elements. This generic communication layer coupled with a plug-in mechanism enables users to implement and add novel elements to the framework. Within these extensions CrusDe supports the reuse of existing elements. CrusDe can be adjusted to new deformation problems with minimal programming and testing efforts. Its modular architecture encourages parts or all of the framework to be included in projects that, for example, need a submodel for isostatic rebound of the crust.

## 1. Introduction

Crustal deformation is concerned with responses of the Earth to endogen (e.g. magmatic) and exogen (e.g. glacial) processes. Here we focus on surface loads disturbing the isostatic equilibrium of the lithosphere. We can think about this as the Earth-load-response-system as depicted in Figure 1. The surface load and its change over time, the load history, represent the input signal of the Earth model – a low pass filter defined by simplifying assumptions about the real Earth. Timescales on the order of a year could be modeled using an elastic Earth, whereas longer intervals would require an additional relaxation function to account for ductile material flow. On the output side of the Earth-load-response-system we observe a transformed lithosphere. Changes affect its stress state, surface displacement and other characteristics that can be quantified by geophysical data.

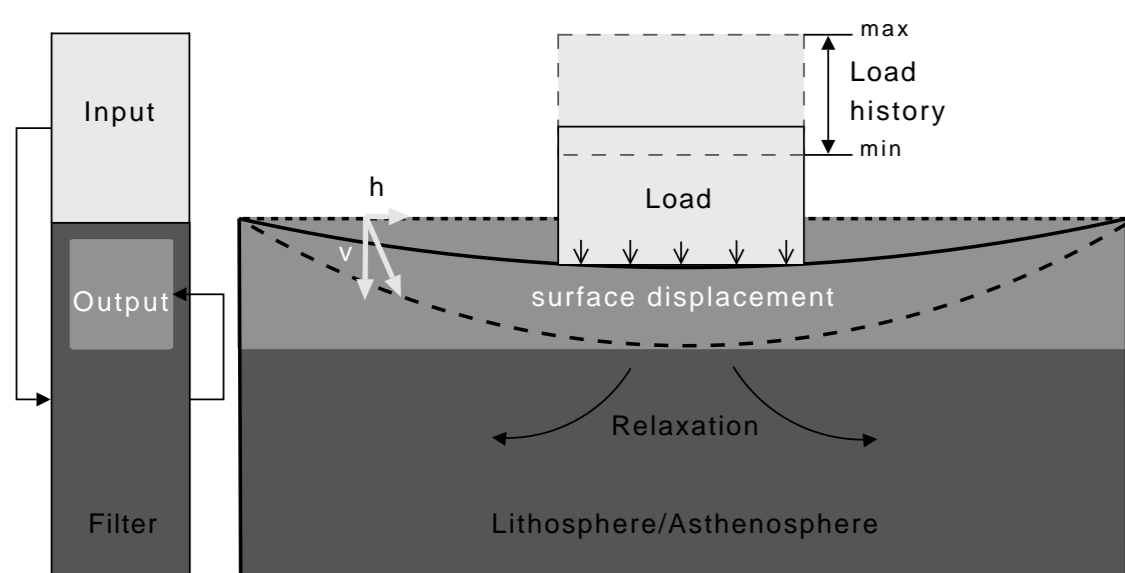


FIGURE 1: Conceptual model of the Earth-load-response system. A load is applied to the dotted black line which represents the initial state of the Earth's surface. The Earth responds to this mass force by surface displacement, changing its state to the one denoted by the solid black line. The load may vary over time which is denoted by a load history. It might raise to a maximum level which results in maximum displacement indicated by the broken line. Relaxation due to ductile material creep has to be accounted for on longer timescales.

## 2. A Generalized Load Response Function

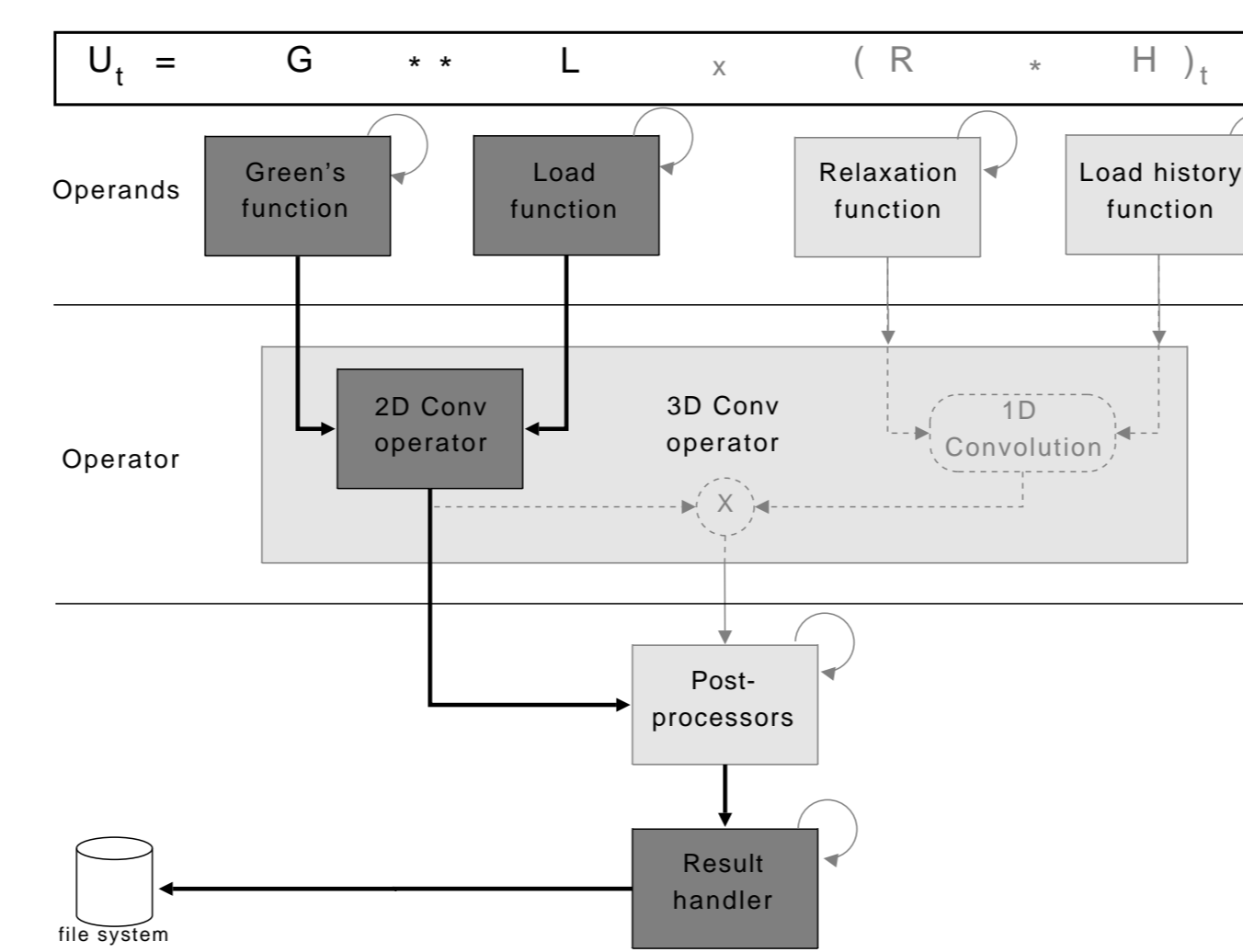
To derive a formal model from Figure 1, we assume the surface load is composed of point loads,  $L$ . Convoluting these with a Green's function  $G$  that represents a unit impulse response of a specific Earth model we can simulate, e.g., the deflection of the Earth's surface,  $U$ . Pinel et al. (2007) derive Green's functions for the instantaneous and final relaxed response to a surface load. Exponential decay serves them as a relaxation function,  $R$ , to realize the temporal evolution of displacement. Assuming the load function can be separated in dependency on space,  $L$ , and time,  $H$ , Pinel et al. (2007) give a solution for displacement rates by including a convolution of the load history,  $H$ , with the relaxation function,  $R$ . This can be generalized to:

$$U_t = \sum_{i=0}^{n-1} (R_i * H_i)_t \cdot G_i * L \quad (1)$$

where  $U_t$  is the displacement (rate) at time  $t$ . The sum allows for superposition of different Green's functions, e.g. adding the elastic to the creep response and the asterisk notation expresses the convolution. The property of the delta function as the identity operator of convolution can be used to remove the load history or relaxation function.

## 3. CRUSDe's Concept and Architecture

The basic idea behind CRUSDe's architectural concept is to transfer the modularized structure inherent to Equation 1 into a simulation framework. Figure 2 shows how the terms are mapped to software components as well as the data flow between the components. The boxes in dark grey with bold arrows mark the minimum of participating software components; elements in light gray are optional. Reflexive arrows denote reuse of components within their category, i.e. a new Green's function can only use other existing Green's functions. An example is shown on the operator level where the 2D convolution operator is integrated into a 3D convolution operation. The summation in Equation 1 is realized by a 'job' mechanism that allows for the



exchange of all operands but the load. Jobs are realized as sequential executions of an experiment with a changed configuration. Experiments are defined in the Extensible Markup Language (XML); an example is given in Listing 1.

FIGURE 2: Mapping of terms in Equation 1 to CRUSDe's software components. Additional components are added to increase functionality and flexibility. Reflexive arrows refer to components that can access functionality of other components of its category. The 2D convolution operator takes data from the Green's and load function. Depending on whether relaxation or load history are defined the 3D convolution must be used which reuses the 2D operator. The result for the examined area is calculated and post-processors can be applied to it. A result handler writes the modeling results in a particular format to the file system or might be used to pass it to a different tool.

To realize this concept, the data flow in figure 2 is expanded to a three layer structure. The software components are included as plug-ins in a Functional layer. This is in accord to their nature of containing the underlying simulation functionality. An Interface and Management layer transparent to the user implement the logical data flow between the individual components and hence add the composability to CRUSDe.

## 4. Conclusions and Outlook

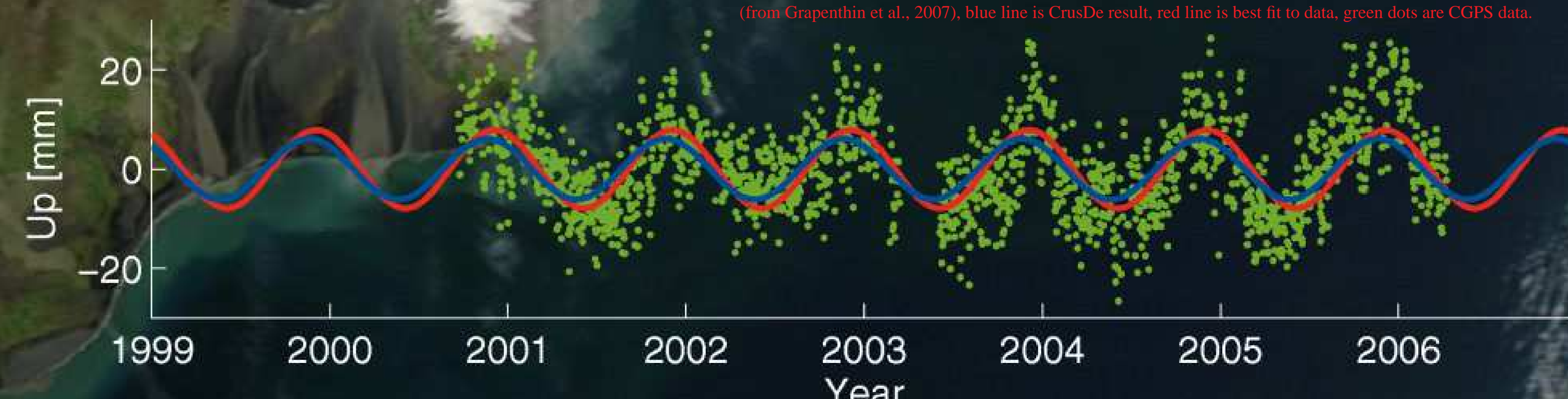
The simulation framework CRUSDe enables the user to (i) dynamically select software components that participate in a simulation, (ii) extend the framework independently with new software components and reuse existing ones, and (iii) exchange software components and experiment definitions with other users. Current Green's function implementations:

- elastic response, final relaxed response, pure thick plate response (all flat Earth)
- Those can be combined to express:
- exponential decay from elastic to final relaxed response, displacement rates due to:
  - one or multiple disk or irregular loads or a combination
- with independent load history and crustal decay functions.

Future developments will focus on including spherical Earth models and using autoconfig tools for the installation procedure.

```
<?xml version="1.0" encoding="UTF-8"?>
<!-- This model is equivalent to the one used in Grapenthin et al., GRL, 2007 to de- -->
<!-- describe the elastic response of the crust to annual changes in the snow load of -->
<!-- Icelandic ice caps. We used a simple sinusoidal function as a load history. The -->
<!-- result shows the elastic response of the crust to the load changes over a full -->
<!-- year. The load maximum is in mid-May (day 140). -->
<!--
<!-- MODEL NAME CONFIG -->
<!--
<!-- MODEL RESULT FILE -->
<!--
<!-- MODEL INPUT CONFIG -->
<!--
<!-- MODEL TIME CONFIG -->
<!--
<!-- KERNEL DEFINITION - we want to do something with time, hence 3d convolution! -->
<!--
<!-- EARTH MODEL (equations 1 and 2 in Pinel et al., 2007, GJI) -->
<!--
<!-- LOAD MODEL - each value of the load history will be multiplied with the -->
<!-- convolution result of the Green's function and the load function. -->
<!--
<!-- LOAD HISTORY - a cosine, define period, set the point of maximum amplitude -->
<!--
<!-- POSTPROCESSORS - here come the things that add a little comfort to the results -->
<!--
<!-- RESULT HANDLER - write data in netCDF format -->
<!--
</experiment>
```

LISTING 1: Example of an XML experiment definition for CrusDe. Output for one CGPS site in Iceland shown in background (from Grapenthin et al., 2007), blue line is CrusDe result, red line is best fit to data, green dots are CGPS data.



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