GIS-SUPPORTED SATELLITE RADAR DEFORMATION MONITORING: POTENTIAL AND REQUIREMENTS

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ABSTRACT

Since the early 1990's, satellite radar interferometry (InSAR) has been used to measure sub-cm deformations of the earth's surface, for example related to land subsidence and tectonic or volcanic deformation. Compared to traditional geodetic techniques for deformation monitoring, which are point positioning methods, the imaging characteristics of InSAR introduce new possibilities in the interpretation of the data. An additional consequence of the imaging characteristics is the fact that deformation that was not known beforehand can now be detected and monitored. Lately, the technique has been refined by exploiting the large data archive of satellite images acquired since 1992. This way, time series processing enables the detection of very small movements, potentially with a precision of 0.1 mm per year, with a spatial resolution of about 20 meters, over areas up to 100 km across.

Although these technical achievements in terms of the observations are the necessary ingredients for a new level of applications, it is paramount that new models need to be developed to link the observations to parameters describing the driving forces behind the deformations. With increasing precision levels, more subtle movements of the earth become detectable. Moreover, in many cases there will be more than one mechanism responsible for the detected deformation. For this reason, geographic information systems become indispensable to systematically combine all possible sources of additional information that may contribute to the model formulation. Interactive and automatic testing procedures need to be developed and included in the GIS environment, and data sources with varying characteristics (spatial, temporal, formats, qualitative, quantitative, two- and three-dimensional) need to be easily integrated in the analysis. In this paper we give an overview of the requirements of such systems in relation to radar interferometry and the potential for improved understanding of processes in the earth's crust. The main focus will be on the urban environment and processes related to land subsidence and water management.

Keywords: InSAR, Land Subsidence, Interoperability, Geo-Information Infrastructure

1 INTRODUCTION

Large scale surface deformation in the Netherlands, such as tectonic tilting or land subsidence due to gas extraction, is relatively well known, based on conventional geodetic methods. Unfortunately, local deformations, e.g. due to ground water level changes, infrastructural works, bad foundation of buildings, or industrial water extraction, are much harder to monitor, since measuring such local deformations requires prior knowledge on their existence, location, and on their driving mechanisms. Second, especially for slowly deforming objects, a time series of several years needs to be established with high accuracy, high spatial resolution, and a dense spatial sampling. These requirements translate directly into costs and, consequently, a high barrier to start such an analysis. As a result many local deformations in the Netherlands remain unknown.

Using satellite radar remote sensing, it is now possible to monitor subtle systematic movements of single buildings with a sub-mm/y precision from an altitude of 800 km [1]. These results are obtained by analyzing the reflections of radar waves from objects at the earth's surface [2]. The spatial resolution is about 10 m, a swath width of 100 km, with a temporal resolution of 5 weeks, and starting from 1992.

Applying this technique to areas in the Netherlands has revealed stunning deformation phenomena such as the sagging of parts of the A10 highway around Amsterdam and the effects of local gas extraction beneath Rotterdam. However, of the hundreds of points/km2 there are many that deform in an unexpected way, making the identification of the driving mechanisms impossible from the data only.

Within the project: “Pin-Point deformation monitoring by satellite radar remote sensing and 4D GIS” a joint analysis of satellite radar deformation data over the Netherlands is foreseen, using GIS technology. Different information sources will be combined (topographical, cadastral, geotechnical, meteorological, and visual information, water level time series, etc) to analyze all relevant information related to a specific observation. For this goal, the radar deformation results need to be tied to the GIS environment, while GIS techniques need to be developed and optimized. This includes OGC-support (enabling the interoperability of research driven datasets), on-the-fly projection (datum shifts) of regional data sets, and solving the problem of confidential datasets (allowing only operations and analyses on datasets via the internet). Most important is the incorporation of the third and fourth dimension within the storage, calculations and visualization of the geo-datasets. This will lead to a combination of information sources that are crucial for understanding the mechanisms behind the observed deformation. The developed methods and algorithms should contribute to the final goal of the systematic and recursive monitoring of deformation in the Netherlands.

2 SATELLITE RADAR DEFORMATION MONITORING

We will illustrate the potential and requirements of applying Satellite Radar Monitoring by the difficulties in correlating groundwater extraction and land subsidence within the province of Zuid-Holland in the Netherlands.

In figure 1 the location of permanent groundwater extraction licenses within “Zuid Holland“ is illustrated. One of the highest extractions is related to biochemical industry activities at Delft (figure 2). It is possible that this extraction is related to local landsubsidence, as illustrated in figure 3.

Figure 1: Groundwater extraction Zuid-Holland

Figure 2: Location of DSM GIST at Delft

If we look into detail (at one of the canals in Delft) the impact of this small deformation (only 5 mm / year) is shown in figure 4, where a period of hight rainfall will result in wet feet.

But are we sure about this conclusion? In this case it could be, cause of the availability of prior knowledge (existence, location, driving mechanism), the null-survey and long time series, the high temporal and spatial resolution, and the time and money to survey (leveling).

The deformation in this example was to a certain extent easy to detect. However, many others, and especially local deformations will be remain undetected as long as time series of leveling data are not present for each building under study.

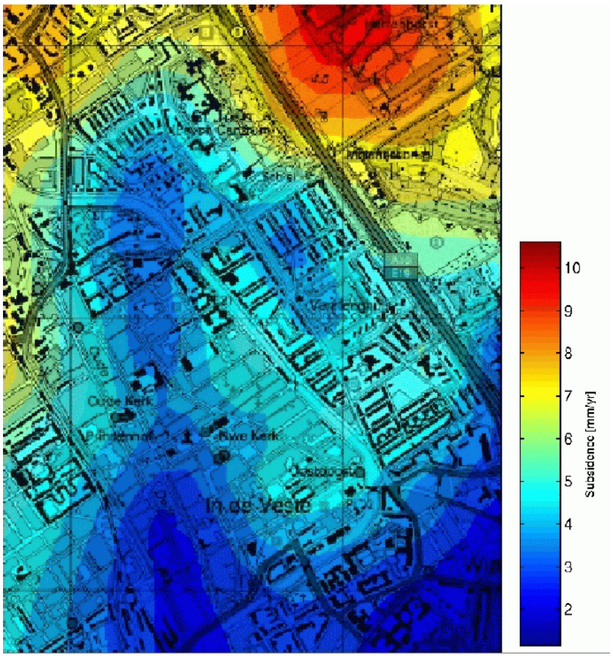

Figure 3: Deformation Delft 1961-1974 (leveling)

Figure 4: Local land subsidence in combination with heavy rain fall leads to extremely high water levels in the canals of Delft

2.1 LOCAL DEFORMATIONS USING SATELLITE RADAR REMOTE SENSING

With the availability of ERS SAR amplitude images this process of detecting local deformations could be made faster, and more important: we can trace deformations that are not so evident as in the first example.

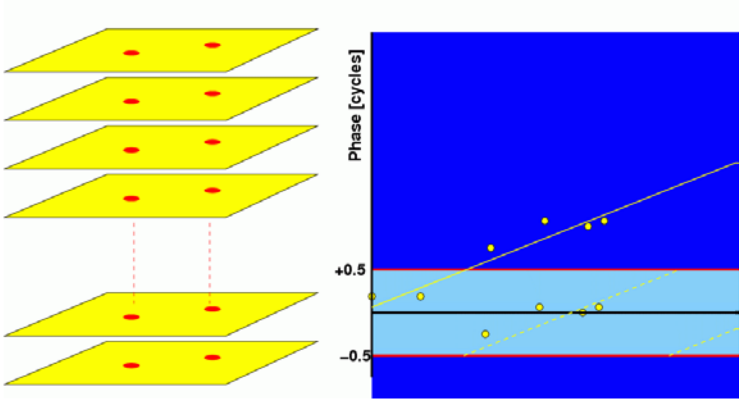

Figure 5: ERS SAR amplitude image of Delft

Figure 6: Reveal deformation out of permanent scatters

From the ERS SAR images (swath width 100km, spatial resolution 10 m, temporal resolution 5 weeks) that are available from 1992 the systematic movement of permanent scatters can be obtained with a mm/year precision, see figures 5 and 6. These permanent scatters are not known beforehand, and not all of them will reveal a systematic trend. But the scatters that do, and are located i.e. at or around buildings will expose a deformation of that building or some area in its neighborhood.

To determine what is moving sometimes a validation within the field is required, see figure 7.

Now the deformation is known, but the driving mechanisms behind this subsidence are not. These local deformations could be caused by ground water level changes, infrastructural works, the building foundations, industrial water extraction, gas, oil, salt exploration, etc. etc. All these possible causes should be identified and taken into account in the deduction (figure 8).

Figure 7: Field test to validate a local subsidence: here it is the premise that is subsiding instead of the building.

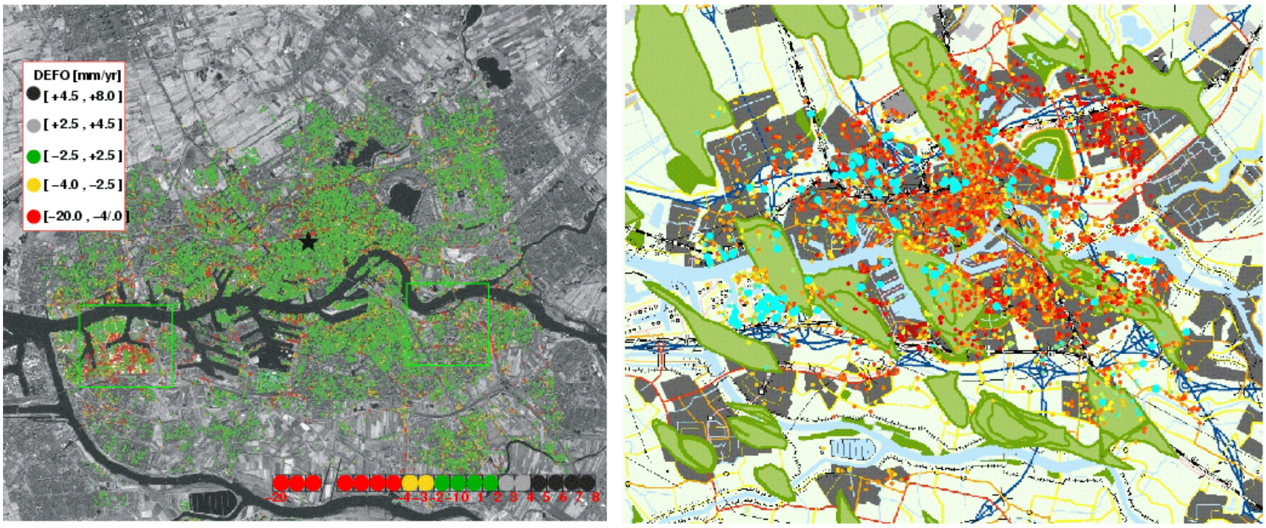

Figure 8: Possible correlation between oil-bearing areas and deformations came across the surface

3 GEO-INFORMATION PROCESS CHAIN

If we want to combine all possible sources of additional information related to the research goal to monitor land subsidence, we come across the well-known geo-information process chain [3]. Based on a common geometric infrastructure (i.e. reference systems), the needed geo-information is collected, modeled and stored within geo-database management systems. Now we can deduct the desired information and an iterative process of analysis and handling, presentation and interaction is started. This process ends when some new results (new datasets, maps) are derived and that we want to exchange to other users or scientists. These others perform a similar, but for their goal intended, geo-information process chain. This will result in unavoidable duplications within the needed geo-information collection, modeling and storage. And more harmful, they could perform some analysis and data handling with the data under study without a real understanding of what is allowed to do, resulting in non-valid or odd outcomes. If these results are exchanged to the community, without giving a clue on the lineage, more strange results are to be expected, without any mechanism to identify this kind of unreliable consequences.

3.1 FROM DATA-PROCESSING TO GEO-INFORMATION INFRASTRUCTURE

To avoid the problems addressed in the introduction, the geo-information application transitions need to be supported by scientific, technological and societal innovations. The four main transactions, as indicated by the Dutch knowledge project proposal ‘Space for Geoinformation’ [4] are:

1. From ad hoc (project) driven geo-information processing to a full Geo-Information Infrastructure;

2. From static ‘maps’ to ‘dynamic’ models of space;
3. From traditional map production to dynamic data collection and positioning on the fly;
4. From implicit semantics of geo-information to explicit knowledge.

The Geo-Information Infrastructure consists of four components:

1. Basic or authentic geo-data sets in different domains: topography, elevation, cadastre, geology, etc;
2. Geo-data processing services in general and the geo-DBMS specifically;
3. Interoperability standards;
4. (Wireless) networks.

The introduction and acceptance of geo-Database Management Systems together with the success of the Internet from the mid ’90 has made an end to the propriety geodata formats and dedicated systems. Now it is in theory no longer needed to trace the data sources firstly and to exchange the available datasets in the format appropriate for the unique system secondly to analyze and visualize the data. When the organizational, financial, technical, etc. issues of the geo-information infrastructure are tackled in theory it should possible to improve this situation by providing:

1. Consensus on the geometric parts of the data model, both raster and vector data have to be supported (including different spatial reference systems);
2. A formal description (meta-data) of the geo-datasets, covering both the spatial and non-spatial aspects;
3. Catalogue services to access and query the meta-data and how the results of such a query is returned;
4. A mean to query the geo-data itself;
5. A Geometric Modeling Language (GML) to format and transfer the resulting geo-dataset.

3.2 BEYOND WEB MAP SERVICES, WEB FEATURE SERVICES AND LOCATION SERVICES

The first visible developments achieved by the geo-information infrastructure initiative are the so-called web map services (WMS) and web feature services (WFS). This kind of services returns on a specified request (map-extent, layers) either a bitmap (.bmp, .jpg), or the vector data (embedded within GML). The users have the guarantee that they have the most actual and complete geo-dataset directly from the source at their disposal, see figures 9 and 10.

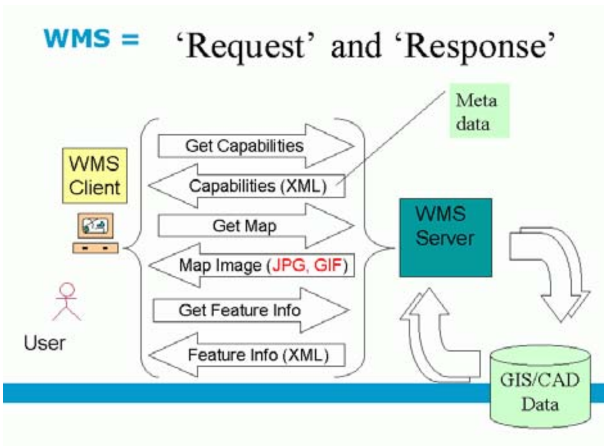

Figure 9 : Web Map Server

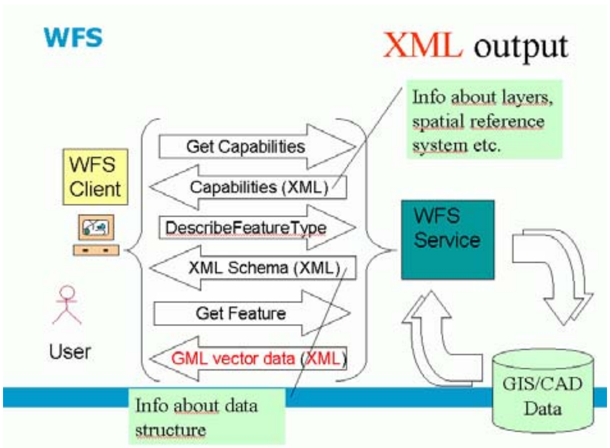

Figure 10 : Web Feature Server

The Open Geospatial Consortium [5] identifies in conjunction to the WMS and WFS services several other location services, all of them client-server based.

1. Directory Service - Find the location of a specific or nearest place, product or service;
2. Gateway Service - Fetch the position of a known terminal from the network;
3. Geocoder Service - Transforms a descriptive indication into a normalized description of the location;
4. Route Service - Determines travel routes (a special kind of WFS);
5. Navigation Service - Determines travel routes and navigation information between two or more points;
6. Presentation (Map Portrayal) Service - Portrays a map up of a basemap (i.e. WMS);
7. Reverse Geocoder Service - Transforms a given position into a normalized description.

This list of services is dedicated to location-based services, with a relative simple functionality. For our purposes we need a more demanding set of geodata processing services, and also means to store the utilized model and repeat the model with other of data or parameters. As noted, the initiatives of the Open Geospatial consortium are promising, but yet not sufficient to deal with i.e. monitoring land subsidence.

Within these kinds of case studies, we will combine several geo-information sources without knowing the added value in doing so beforehand. One way to deal with this manner is to utilize the map-use-cube, as introduced by MacEachren and modified with Kraak [6] in mind. This cube (figure 11) contains three dimensions: private to public, high interactivity to low interactivity, and revealing knowns to exploring unknowns. Traditional cartography has emphasized public use, low interactivity and revealing knowns, while visualization emphasizes private use, high interactivity, and exploring unknowns (though perhaps without ignoring presentation of information). So we will visualize these datasets in such way that they will hopefully reveal some information to us. We will process the data not according to various fixed rules, but by trial and error, resulting in some knowledge about cause and effect. We will consult some other related disciplines to discuss what is on the map. And finally we will produce a map, fit it on a poster or presentation, add some notices and have some discussion with others on this scientific judgment during a workshop.

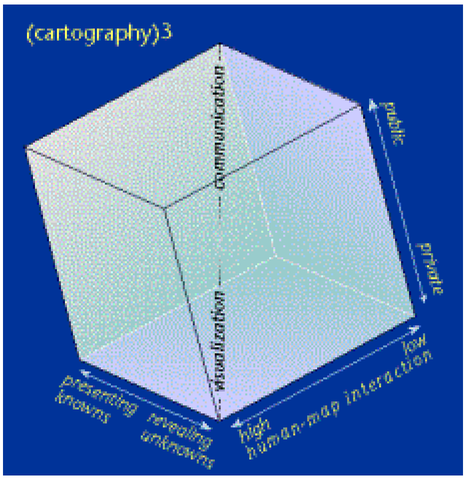

Figure 11: Map-use-cube - from visualization to communication

Kraak [7] discusses these relations between the fields of cartography and GIS, on the one hand, and scientific visualization on the other. He states:

> "Geovisualization integrates approaches from scientific visualization, (exploratory) cartography, image analysis, information visualization, exploratory data analysis (EDA) and GIS to provide theory, methods and tools for the visual exploration, analysis, synthesis and presentation of geospatial data. In this context, it is required that cartographic design and research pay attention to human computer interaction of the interfaces, and revive the attention for the usability of their products. Additionally, one has to work on representation issues and the integration of geocomputing in the visualization process. As such, maps and graphics are used to explore geospatial data and the exploration process can generate hypotheses, develop problem solutions and ultimately construct knowledge. In a geovisualization environment, maps are used to stimulate visual thinking about geospatial patterns, relationships, and trends. One important approach here is to view geospatial data sets in a number of alternative ways, e.g., using multiple representations without constraints set by traditional techniques or rules. This should avoid the trap described by Finke [8] who claim, "most researchers tend to rely on well-worn procedures and paradigms..." while they should realize that "…creative discoveries, in both art and science, often occur in unusual situations, where one is forced to think unconventionally." This is well described by Keller and Keller [9], who in their approach to the visualization process suggest removing mental roadblocks and taking some distance from the discipline in order to reduce the effects of traditional constraints."

Although this might be true, and most of us work this way, we all know that - getting back to our land subsidence-monitoring example - after some month we have forgotten the way we processed the data, the data itself is accidentally removed from the disk, and the researcher who has performed essential parts of the study has moved to another university. The only source left is the poster or a paper; both not intended to store the process information, but only a summery of the results. Maybe it is not at all times so destructive, but in the case of doing a study repeatedly with new available data, it should be made possible to perform the analyses exactly the way it was done before.

3.3 WHAT WE NEED: INTEROPERABLE GEOSPATIAL PROCESSING SERVICES

Here is how a geo-information infrastructure in conjunction to a proper geospatial processing management tool can help us to beat this trap. One way to achieve the 'freedom in limitation' is to optimize and develop the use of geospatial webservices in such way that these services can perform more complex and dedicated manipulations and analysis directly at the server side. Particularly image processing is one of these matters. It doesn't make sense to copy Gigabytes of images, when only a small segment out of that is needed, or to invest in dedicated software with functionality applied only once during the project. When these functions are made available at the server-side, and the data needed is also stored somewhere where it belongs, the client could just receive what is asking for. Another example could be the access to nation wide topographical databases. Querying these databases by a WMS or WFS client is a first step, but the functionality is limited to just a map or – more useful – to the data itself. One could think of geospatial processing services that process the available data that reside somewhere at the place where it belong, the data stakeholder. The route and navigation services specified by the Open Geospatial Consortium are fine examples, but these cases could be extended to the full range of functionality available within desktop GIS.

The advantages of this approach are not only convenient within the availability of these tools, but also in within the description and standardization of the interfaces, also known as: interoperability, see figure 12.

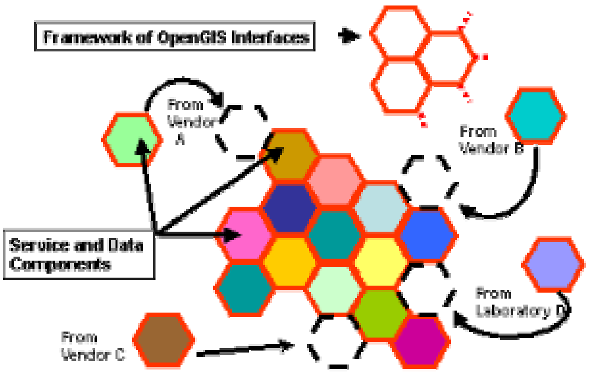

Figure 12: Framework of OpenGIS Interfaces

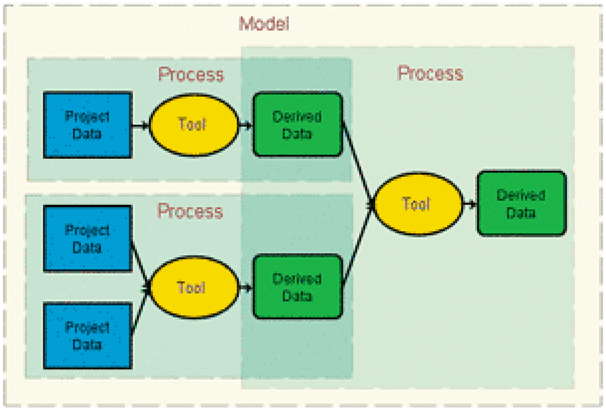

Figure 13: ModelBuilder to control processes

Besides, the geoprocessing management tools have to be developed to keep the data-flow and geospatial processing services under control. These tools, like the ESRI Modelbuilder [10], figure 13, "provides a graphical modeling framework for designing and implementing geoprocessing models that can include tools, scripts, and data. Models are data flow diagrams that link together a series of tools and data to create advanced procedures and work flows. ModelBuilder is a productive mechanism to share methods and procedures with others within, as well as outside, your organization."

A next step is the adaptation of sensor-webs within this kind of geospatial research. Mark Reichardt [11] states the possibilities at the website of Geospatial Solutions: According to Kevin A. Delin of NASA's Jet Propulsion Laboratory, "the Sensor Web concept enables spatio-temporal understanding of an environment through coordinated efforts between multiple numbers and types of sensing platforms, both orbital and terrestrial, both fixed and mobile. Each of these platforms, communicates with its local neighborhood of sensors and thus distributes information to the instrument as a whole. The Sensor Web is to sensors what the Internet is to computers, with different platforms and operating systems communicating by way of a set of robust protocols."

4 CONCLUSIONS

Within this paper we have focused on the potential and requirements of GIS-supported satellite radar deformation monitoring. First of all it should be concluded that deformation monitoring using radar interferometry reaches a higher level of precision as it can detect sub-mm/year subsidence of permanent scatters. However, as this information becomes available it introduces a need to investigate a large range of physical mechanisms that may play a role in the deformation. A wide range of information sources expresses these mechanisms, i.e. water management, local shallow and deep geology, construction foundations, meteorology, geodetic observations, photography, etc. To understand the impact of a physical driving mechanism on the deformation measured, these information sources should be available for exploration and analysis by visual interaction and interactive visualization as offered by geographical information systems.

We recommend a proper adoption of the geo-information infrastructure within this kind of geo-spatial research. When basic or authentic geo-data sets are available in an open, interoperable environment, one can focus on the systematic and recursive routine study needed to show a relationship between the examined deformation and the driving mechanisms. The computation itself should also be as open and clear as possible, which can be reached by the use of geo-processing services and schematizing the calculations within a kind of a model builder. By publishing not only the results of the research, but also the steps undertaken to get these results and the possibility to rerun the model with other data a real understanding of the observed deformations will be come insight.

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