

Beyond Visualization

Designing Interfaces to

Contextualize Geospatial Data

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Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
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Abstract

The growing sensor data collections about our environment have the potential to drastically change our perception of the fragile world we live in. To make sense of such data, we commonly use visualization techniques, enabling public discourse and analysis. This thesis describes the design and implementation of a series of interactive systems that integrate geospatial sensor data visualization and terrain models with various user interface modalities in an educational context to support data analysis and knowledge building using part-digital, part-physical rendering.

The main contribution of this thesis is a concrete application scenario and initial prototype of a “*Designed Environment*” where we can explore the relationship between the surface of Japan’s islands, the tension that originates in the fault lines along the seafloor beneath its east coast, and the resulting natural disasters. The system is able to import geospatial data from a multitude of sources on the “*Spatial Web*”, bringing us one step closer to a tangible “*dashboard of the Earth*.”

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1. Introduction

A growing armada of satellites is streaming high-resolution imagery of the electromagnetic spectrum back to our planet's surface, continuously sharpening our perception of the world and the complexity of its systems. At ground level, innumerable sensors log every aspect of terrestrial activity—from seismic waves to the facial expressions of pedestrians walking through the city. Meanwhile, most of us carry in our pockets a tiny box filled with sophisticated sensing hardware connected to mobile antennae; essentially forming a crowd-sourced, global sensor network that is converting the “*physical world to a digital model*” (Meng 2010).

As this model becomes more fine-grained, it has the potential to drastically change our perception of the world. Indeed, when the first photograph of our planet as seen from a distance of 45,000 kilometers reached us in the early 1970s, it had an unprecedented psychological impact. People felt deeply moved by this radically new, exocentric view onto their own habitat. Dubbed the “Blue Marble”, this photograph of planet Earth was iconic “*because it perfectly represented the human condition of living on an island in the universe, with all the frailty an island ecosystem is prey to*” (Petsko 2011).

Not only is the world that surrounds us extremely data-rich, there is also an abundance of complex systems, many of which we have not even begun to understand completely. Phenomena such as global warming and natural disasters have intertwined interactions and cause-and-effect chains. The more we learn, the more this island's fragility should become obvious to us. As the National Science Foundation states, “*even modest changes to Earth's systems have had profound influences on human societies and the course of civilization ..., understanding*

these systems and how they interact is vital for our survival” (NSF 2010).

In recent decades, natural disasters appear to occur with higher frequency, while technological progress has enabled geographically dispersed groups of humans to connect informally and share data without restraint. This has led to self-organized groups that have made it their mission to collect environmental data and make it publicly available to enable discourse and analysis, such as the *Safecast* project. Such groups aim to inform the general public about emerging risks through “crisis mapping”, with the intent of building more resilient societies that are able to prepare for and manage disasters more efficiently.



Figure 1: Rockslide of Elm, 1900. Albert Heim. Collection Department of Earth Sciences ETH

To make sense of all this data, we commonly use visualization techniques, because we want to reveal patterns and render previously unseen information visible. Many software tools and interactive systems have been developed for scientific visualization. Most of these systems are limited to post-processing of datasets, and the final result is often another dataset, which today typically becomes available for public download and will be further processed and visualized by other interested parties.

The increasing popularity of data visualization suggests that there is great value in revealing the visual patterns beneath the raw numbers, so that they may be grasped intuitively. Visualization is especially useful for scientific analysis, as when *“drowning in data ... visual techniques provide a first line of attack that can suggest what kind of trends and patterns may lie within the numbers, and may thus help guide the focus of more detailed analysis”* (Ball 2002). Yet as we amass very large datasets, the lessons that a less informed, but curious public might actually learn from graphical visualizations are not always evident. For instance, when visualizing the relationships in a complex network, maintaining readability is enormously challenging, since *“when networks are large, consisting of thousands or millions of nodes, node-link diagrams can become so overwhelmingly cluttered”* (Dunne and Shneiderman 2012). In the case of spatial sensor data such as radioactive contamination levels or earthquake frequency, where datasets typically contain hundreds of thousands to millions of readings, are two-dimensional map visualizations sufficient to educate laypeople about the underlying problems, risks and patterns?

While we won't be able to prevent natural disasters, their devastating effects can be partially mediated by propagating general preparedness. It seems obvious that *“cultural awareness”* is key to saving lives in situations of disaster, as a *“lack of [it] in crisis situations generates potential for an unnecessary injury or*

loss of life” (CSSES 2011). Threats to life or property “*can be reduced by identifying high-risk locations and minimizing human habitation and societal activities in them, improving construction methods, developing warning systems, and recognizing how human behavior influences preparedness and response*” (NSF 2010).

The hypothesis that novel interactive systems are an effective means for educators to foster conceptual change and create responsible future generations remains—due to its broad scope—not objectively testable. However, we can establish with certainty that “*an Earth-science-literate public, informed by a current and accurate understanding of the Earth, is critical to the promotion of good stewardship, sound policy and international cooperation*” (NSF 2010).

Moreover, a recent study has shown that physical representation can indeed increase performance and improve cognitive tasks, such as information retrieval when engaging with data visualizations. The authors conclude that “*physical touch seems to be an essential cognitive aid ...*” (Jansen, Dragicevic, and Fekete 2013). We can thus assume that to fully utilize environmental data collections in an educational context, using tangible interfaces to visualize data is a route worth exploring.

Hence, the main questions throughout this thesis will be: how should we design a part-digital, part-physical system that aims to educate the concerned public about the mechanisms that shape the environment they live in, and the concepts and data that allow us to explain these mechanisms? When it comes to understanding complex systems and causality chains—for instance the dramatic events following the 2011 Tōhoku earthquake and tsunami leading up the Fukushima nuclear disaster in Japan—how can we find more engaging ways of interacting with geospatial data that go beyond static visualization?

2. Related Work

2.1. *Tangible interfaces and terrain rendering*

Regarding this area of research, the project most closely related to the contributions of this thesis work was created by researchers at North Carolina State University, who combined *Illuminating Clay* (Piper, Ratti, and Ishii 2002) with “*geographic information systems (GIS) and numerical models of landscape processes*” (Mitasova et al. 2006). The authors emphasize the intuitiveness of physical terrain models, which they use in conjunction with Piper et al.’s system to project live simulation data generated by the free *GRASS GIS* software on top of a clay landscape model.

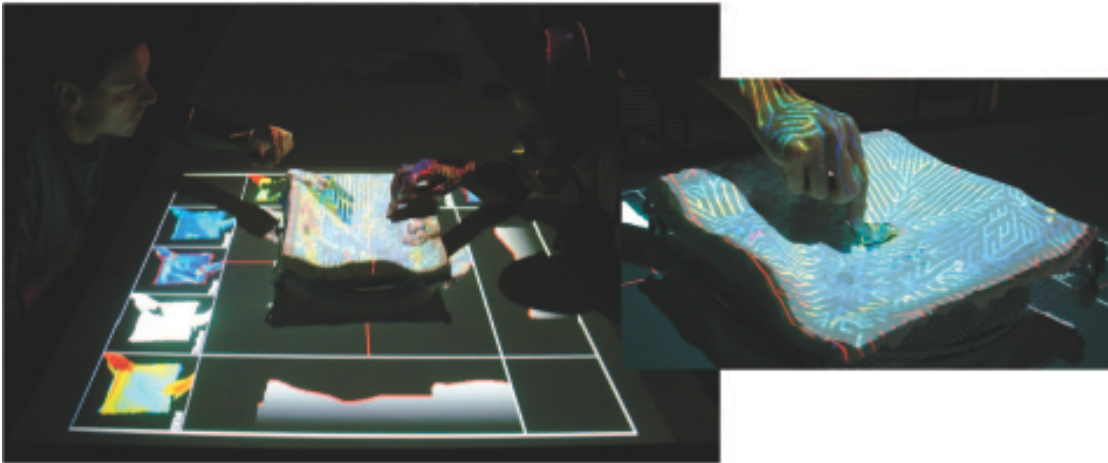


Figure 2: Illuminating Clay coupled with simulations generated by GIS software (Mitasova et al. 2006)

The researchers summarize that “*understanding topography ... is fundamental for many disciplines and provides the driving force for research and development of terrain analysis and visualization tools.*” For future applications, they envision that such augmented terrain models could receive “*real-time data from satellites and terrestrial sensors*” to create systems that

“will not only help us solve day-to-day land management problems, but also improve response to natural disasters and emergencies”, which is precisely the general direction of the application prototypes described below.

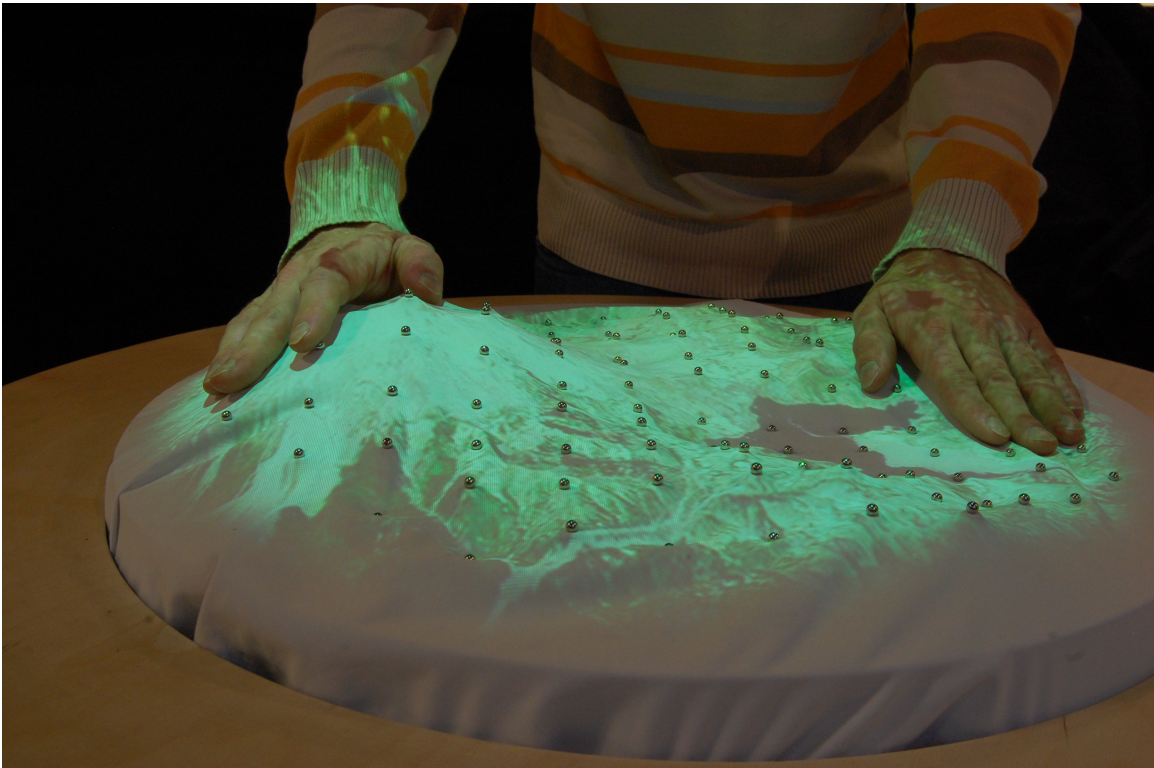


Figure 3: Relief – a scalable actuated shape display (Leithinger and Ishii 2010)

Parts of the work described in this thesis are a contribution to prior work of Leithinger et al., who have been addressing the challenges of partially physical rendering high-resolution geometry on the limited resolution of current 2.5D shape displays. We have recently expanded these physical displays with hovering graphics to explore *“how both digital models as well as handles and controls can be rendered either as virtual 3D graphics or dynamic physical shapes, and move fluidly and quickly between these states”* (Leithinger et al. 2013). The pro-

ject described under Sublimate Terrain Model was an integral component of these efforts.

A team of geologists and computer scientists at *UC Davis* is also exploring novel kinds of environmental data exploration to assist in situations of crisis. They are implementing “*virtual reality data visualization to analyze massive amounts [...] of multiresolution terrain data during the rapid scientific response to a major natural disaster*” (Cowgill et al. 2012). This system is not targeting novice users and is not designed for an educational context, but rather enables “*virtual fieldwork*” for expert users assessing the extent and cause of large earthquakes. As opposed to the main work of this thesis, which integrates physical representations of terrain with overlaying graphics, their application utilizes the *KeckCAVES* immersive visualization environment and does not employ any kind of physical rendering.

The display of real-time geospatial information has also been explored in artistic and exhibition design contexts. A prominent example is Takemura’s *Tangible Earth*, first shown at the 2005 World Expo in Aichi, Japan, a touch sensitive half-spherical display that integrates several real-time data feeds and displays them as textures on a spherical display that can be “spun” on a virtual axis through touch interaction. “Tangible” in this context has to be understood as the “*synthesis of analog and digital elements*.” Other researchers have explored similar spherical interfaces in recent years. One notable example of a completely spherical touch screen was presented by Benko et al. and featured a number of applications previously seen on the flat *Microsoft Surface* tabletop system. They implemented a number of new interactions that were specific to the spherical geometry of the device. Most notably, you were able to “push” a digital artifact (for instance a photo) into the globe and make it appear in the other side, a technique they called “*pushing to the dark side*” (Benko 2009). They also men-

tion that while “*most of the current applications are ill-suited for such non-traditional surfaces*”; these surfaces offer interesting new features. For instance, they noted that while a spherical interface essentially allows a larger group of people to interact at the same time because participants they can stand around the interface, they also mention new concepts such as a form of “pseudo privacy”, where due to the curvature of the surface a person can’t see what another person is doing.

As with many other multi-user touch screens, this setup exhibits problems when the actions of individual users collide, since the system is not able to discern which person a fingertip belongs to. The display prototypes presented by Grossman et al. take another route. The group implemented an actual volumetric display for viewing three-dimensional models. Users were handed wand-like, physical tools to perform manipulations on the scene by pointing and gesturing. This tackles the aforementioned intra-user conflicts and also allows users to actively collaborate: For instance, if users “*colocate their tools, the [...] effect is amplified*” (Grossman and Balakrishnan 2008). However, these tools were not immediately understandable without instruction and reduced the advantages of the display as opposed to a system that allows for direct manipulation. For instance, there were originally two separate tools for zooming in and out, and even after several design iterations “*users found it hard to use the zoom-in tool*” because they were not at all used to the way it operated. A conclusion of both of these projects is that spherical or volumetric display systems are not likely to replace flat surfaces, but can complement them for very specific, custom applications where the physical properties of the interface add useful interaction modalities.

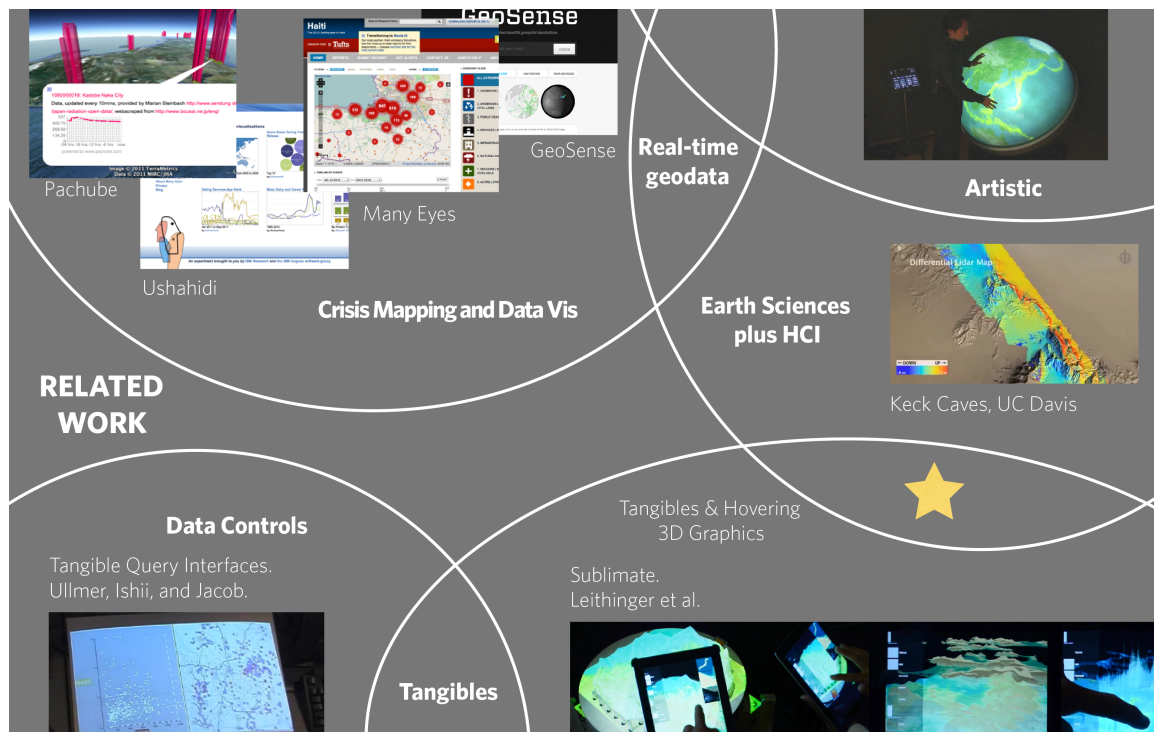


Figure 4: Map of related work and overlapping design spaces

The application prototypes described in this thesis differ from the above setups in that the focus does not lie on rendering spatial information on spherical displays or multi-user touch screens, but rather on its partially physical representation and on the interaction techniques that allow us to “explode” the model and explore its various layers in a hybrid interface that employs principles learned from Tangible Interfaces as well as Augmented Reality.

2.2. Crisis mapping and environmental data visualization

In the larger context of crisis mapping and environmental data visualization, a number of organizations have made efforts to integrate real-time information about environmental factors and essential resources on online maps, and inform the public about emerging disasters, as well as past events.

An especially visible example in this area is *Ushahidi*. The organization advocates crowd-sourced data collection, and it distributes a set of tools to collect and publish data on the web.

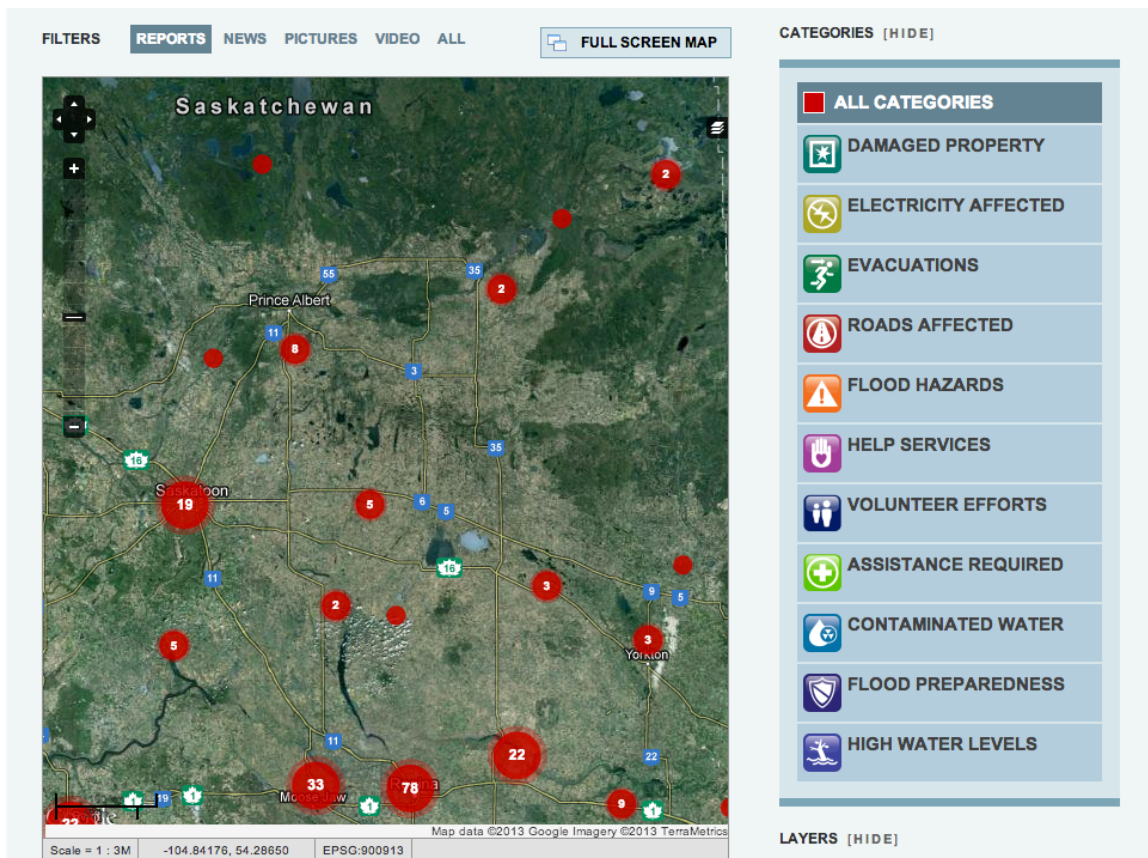


Figure 5: Screenshot of Crowdmapper (Ushahidi platform) of a crisis map for the Saskatchewan floods, 2013

Reduced to their core functionality, such platforms give people the tools to make and publish their own maps, based on data they collect autonomously.

Often used for disaster relief and in political contexts, such technology has generally been met with enthusiasm and high hopes as far as its potential impact on humanity is concerned, but it has also been criticized. For instance, a report that looked at a crowd-sourced oil spill crisis map came to the conclusion that the map “*clearly illustrates a gap in the federal response*” (Dosenmagen and Rolfes 2010).

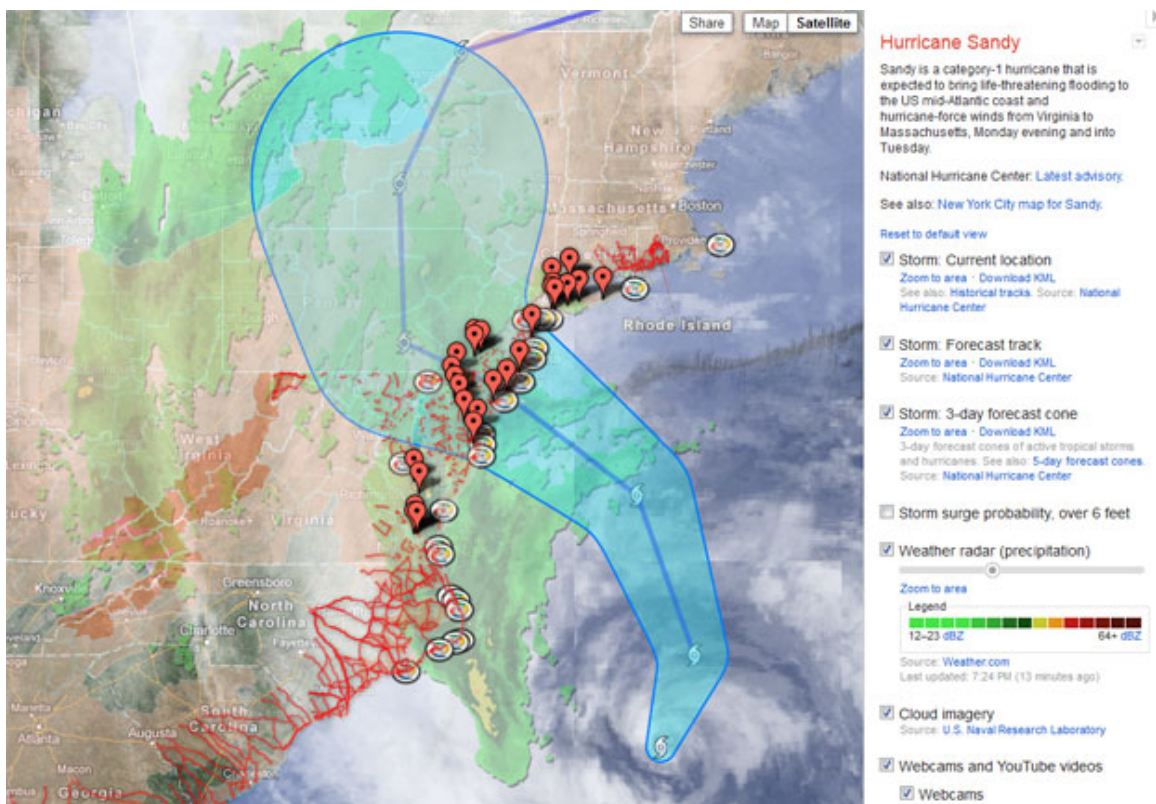


Figure 6: Screenshot of the Google Crisis Map for Hurricane Sandy, 2012

However, when analyzing crowd-sourced mapping platforms “*it is routinely argued that the process of producing and using geographical information has been fundamentally democra-*

tized.” This in turn “evokes ideas about participation, equality, the right to influence decision making, support to individual and group rights, access to resources and opportunities, etc.”—but depending on the definition of “democratization” this technology “becomes far less exciting and transformative” (Haklay 2013). Such criticism notwithstanding, some technology companies have pushed in the same direction, for instance *Google*, who has been providing such maps through its “tech-driven philanthropy” arm.

Our team has also been involved in such efforts through collaboration with *Safecast*, a non-profit organization that aims to provide “a global sensor network for collecting and sharing radiation measurements to empower people with data about their environments.” When data collection is automated or crowd-sourced, the resulting data volume can quickly reach a level where numerous challenges arise, from a technical perspective as well as through issues related to cognition and usability. Visualizing millions of geospatial data points in interactive contexts is a problem that, during precursory work leading up to this thesis, we first addressed when implementing a visualization platform for the data that *Safecast* had collected and needed to publish on-line (see *GeoSense*). The motivation of this thesis partially arose through this collaboration, which continues to date through the *Safecast Air* project that aims to inform communities about air quality and pollution. Moreover, geospatial data tools that we originally created to visualize the *Safecast* radiation dataset were repurposed and extended during the course of this thesis work in order to process and visualize datasets later shown in the *Stratarium* installation.

3. Precursory Projects

Leading up to the main contribution of this thesis work, which is described in chapter 4, *Stratarium*, three relevant precursory projects will be discussed.

The first project, *GeoSense*, is relevant to this thesis since its backend tools were applied as a “data engine” to process and prepare the geospatial datasets used by all of the application prototypes described below (see Implementation Details), and because it is a good example of the problem space of data collection and potential misinformation due to data visualization.

The second project presents a first attempt at interacting with the same datasets within the user’s physical space, and a horizontal exploration of the interaction techniques made possible in the resulting screen-and-tangibles configurations. The third project iterates on this idea, but uses a shape display for physical representation.

3.1. GeoSense

GeoSense is a universal, low-threshold web platform that enables beautiful visualization, sharing, and data analysis of large collections of geospatial data. It uses *OpenStreetMaps* or other providers of map tiles as its base layer, and superimposes geospatial raster or vector data, the design and in-browser rendering of which users are able to customize through a graphical user interface. Originally developed by Anthony DeVincenzi and Samuel Luescher as part of the former's thesis work (DeVincenzi 2012), its initial version was intended as a tool for post-disaster recovery following Japan's 2011 nuclear crisis. It is currently used to render millions of radiation data points that have been collected by volunteers, and it will also be utilized for the upcoming *Safecast* air quality measurement initiative.

3.1.1. Project Background

On March 11, 2011, a magnitude-9 earthquake off the coast of Japan caused a cascade of events that ultimately lead to the explosion of a nuclear reactor near the city of Fukushima, and the release of a substantial amount of radioactive material. In the wake of this disaster, the Japanese government immediately defined a thirty kilometer exclusion zone that people were required to evacuate, but subsequently did not release much information on actual contamination levels around the evacuated areas. Many concerned citizens felt they were not receiving essential information that would enable them to take appropriate action, and there were allegations of collusion for the protection of economic and political interests between the authorities and *TEPCO*, the company that managed the reactors. Indeed, as was later discovered, radioactive contamination was soon observed far outside of the exclusion zone (Brumfiel 2011).

This is why a group of technology specialists and hackers dispersed around the globe founded an organization they called *Safecast*, a “people’s initiative” to make impartial information on contamination levels publicly available. *Safecast*, whose efforts the *MIT Media Lab* was involved in early through its director Joi Ito, started attaching custom-made Geiger counters to cars and driving around the exclusion zone and later also other parts of the country. The organization has since collected over 8 million data points, some of which inside the exclusion zone that have a peak value of over 11 thousand counts per minute, which is the equivalent of 33 Microsieverts/h, compared to an average natural background radiation of about 50 cpm in the rest of the country.

The complete dataset is continuously being made available for download to enable public discourse and analysis. Several individuals soon created various kinds of map visualizations of varying focus and quality, and our team at the *MIT Media Lab* eventually began leading the visualization end of these efforts through the *GeoSense* project to create an always up-to-date official map of the *Safecast* data collection.

3.1.2. Implementation Details

The technical implementation of this web application turned out to be challenging mainly due to the fact that we were not able to render the original millions of points on end user’s devices because of bandwidth and web browser performance limitations. In the case of such a large dataset, the goal is to reduce the number of data points to only a few thousand for any given section of the map.

To achieve this, we use a technique called *MapReduce* which, generally speaking, involves a “map” step that takes a large number of entities as input and maps them to a common key (not to be confused with “maps” as in a visual representations of geography, which are also part of this project), and a “re-

duce” step which groups related entities and determines peak values and averages, thus reducing their total number for output.

Specifically, for our map view we divide the full map area into a grid of squares whose side length is inversely proportional to the zoom level of the map, i.e. as we zoom in, our grid becomes more fine-grained. Our key or common denominator of all points thus is their rounded latitude and longitude divided by grid size. For each grid cell we output the total number of data points for any given collection, as well as their average value.

Since the initial *MapReduce* process for a large amount of data takes a long time to complete, we store a pre-aggregated version of the original data at 20 zoom levels, which enables short load times and fast drawing for seemingly arbitrary map sections. However, when more data is subsequently added to a collection we are able to just re-map and reduce the new data with our existing aggregates. For time-based views such as graphs, a further *MapReduce* takes as input a set of location-grid cells and maps them on a time grid, whose resolution varies from one day to a full year. This reduces the number of points even further and enables us to quickly generate value over time diagrams for the points on any visible map area.

3.1.3. Implications and Criticism

The resulting map now covers large areas of the country, and serves as a baseline model of current radioactivity levels, which will help us determine the effects of such accidents in the future with great accuracy. Unfortunately, such data was not available before *Safecast* started collecting it. However, examining the map today we can see how contaminated material leaked out far beyond the original exclusion zone (Safecast 2013), and large regions will likely remain uninhabitable for decades to come. Perhaps even more startlingly, in recent months we have been able to observe how a suburb of Tokyo

began to exhibit elevated radioactivity levels in the range of over one hundred counts per minute, the equivalent of about 1.8 Millisieverts per year.

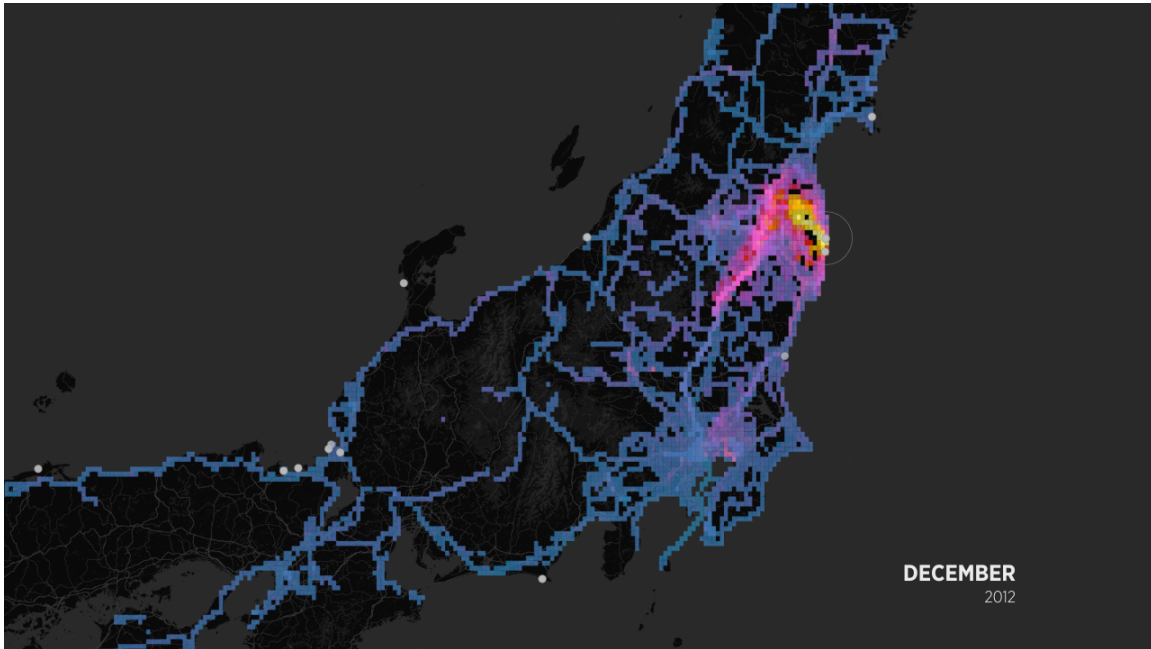


Figure 7: Visualization of the 8 million points in the Safecast dataset as of December 2012

Although still far below the allowed thresholds where there is some evidence for health risks, it is only about ten times lower than the allowed dose for nuclear workers, which is 20 Millisieverts per year. Consequentially local authorities saw themselves forced to dig up playgrounds and replace soil in the affected areas.

However, in the case of the *Safecast* map it becomes especially obvious that there are shortcomings to merely providing map visualizations to the public, without educating users about the consequences these readings may have for them personally. We can easily display on maps which areas are affected and how the contamination is spreading over time, which is a cause for great concern—however, the actual effects are not entirely clear (see Figure 8: Possible Effects of Radiation).

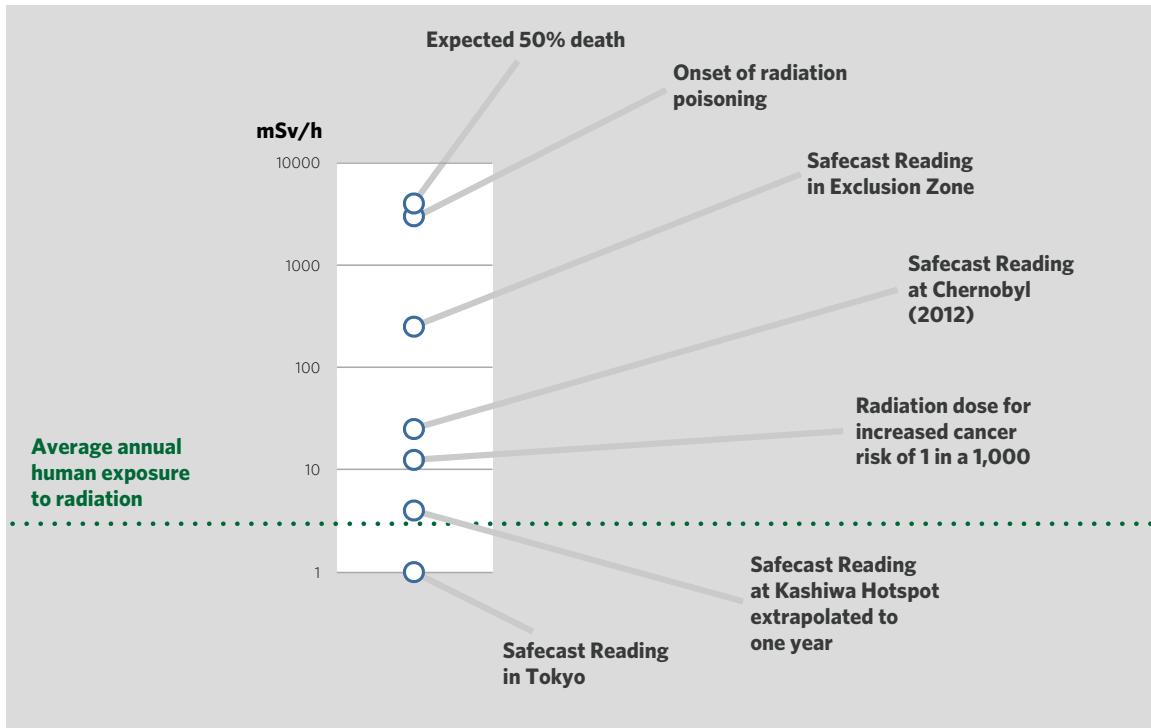


Figure 8: Possible Effects of Radiation

Clearly there is a great need to contextualize such information because the effects of long-term exposure to radioactive material are complex, and a balance needs to be found between informing the public about the measurable facts and educating it about possible risks and actual threats. However, it is important to note that *Safecast* deliberately does not publish such information. The organization maintains that its core activity is the collection and impartial publishing of data about our environment, with the intent of giving the public a tool to help with making informed decisions.

3.2. **Tangible/AR Browser**

When it comes to viewing massive amounts of geospatial data from different sources on a two-dimensional map, the traditional weaknesses of a mouse-controlled graphical user interface become especially apparent. As a first attempt at breaking the geospatial data out of the confinement of a two-dimensional browser window, and putting it in a spatial context that a user can understand more intuitively, a number of different interaction paradigms were explored.

Based on the same datasets that we superimposed in the contextual *Safecast* map, we introduced a setup consisting of the web application, a physical globe on a stand, a number of tablet computers and a larger master screen, where each component can be tethered to one or several of the other components and freely configured to serve as an input/output device among a number of modalities. For instance, a tablet can serve as an AR lens superimposing digital information on the camera image, but it can also serve as a virtual magnifying glass presenting an enhanced digital version of what it is pointed at, and furthermore it can serve as a remote control for a larger view that is presented on the master screen. By coupling the physical affordances of the object with an AR application for tablet computers, we expect to tackle a number of usability problems that commonly occur with mapping applications. We explore possible interaction techniques when coupling tablets with the globe and using them for individual navigation around the geospatial data, subsequent decoupling of specific map views from the globe and the tablet; using the globe as a master control for larger views; as well as basic gestural interaction with the globe.

3.2.1. Implementation

The spinning globe on a stand has long been a popular device for getting a sense of how our planet looks. It is intuitive and easy to use. Relief globes in particular allow for a beautiful haptic experience. In contrast to the problems with digital maps mentioned above, a group of users standing around a physical globe get a very good sense of what portion of the planet they are looking at. They can easily adjust their viewing angle and their proximity to the object by walking around it. Alternatively, they can spin the earth on its axis, which simultaneously changes the view for all users.

Our system consists of a large, physical globe that is tagged on its axis so that we can monitor its exact position with a motion tracking system; a number of tablets that are tracked in the same way; as well as a web application that serves geospatial data and renders map views. Since the application can be accessed with a regular web browser, we are essentially capable of running it on any operating system. We render three-dimensional views of the globe using *WebGL*, which is supported on current tablet devices. This enables us to use the same application for rendering data on a desktop system and the AR application running on a tablet computer. When pointed at the globe, the latter serves as an “active lens” and renders a transparent view of the data, superimposed on the camera image of the physical globe.

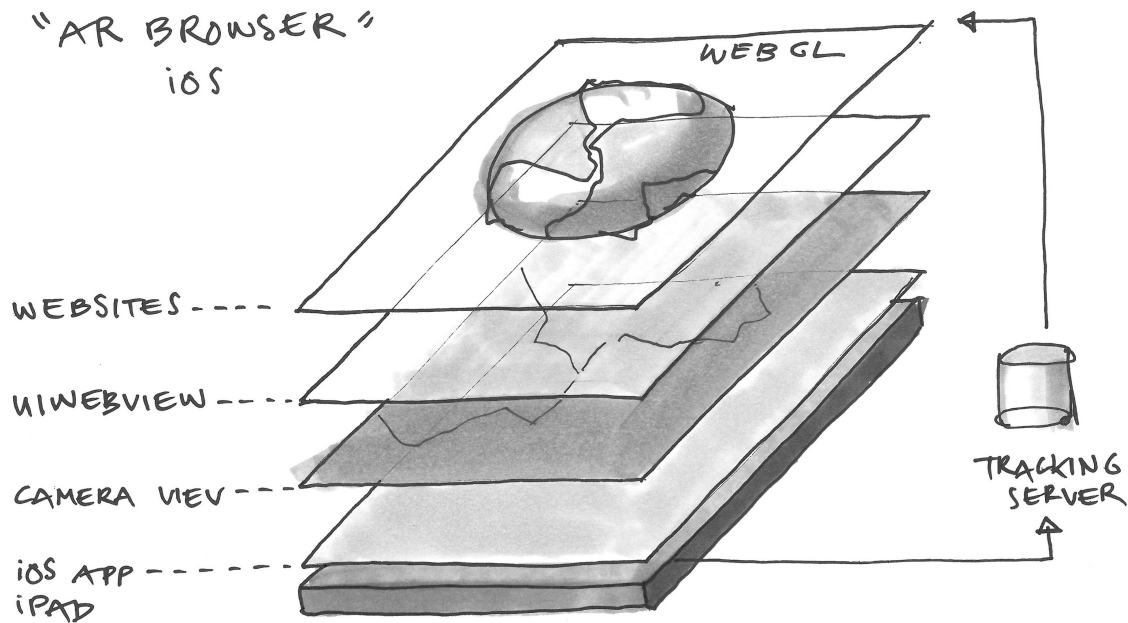


Figure 9: Sandwiching different data views in the Tangible/AR browser project

The technical challenge for the tablet application was implementing a web browser that can display transparent web pages on top of the native camera image, as well as connecting the web application to the tracking server delivering spatial information the devices and/or users that are involved in the current configuration.

A result of this project was the *AR Browser*, a small iOS application that renders the sandwiched view elements and implements a number of hacks, which enable us to render transparent *WebGL* views on top of the camera image.

Connectivity to the tracking server was implemented with web sockets, which we use to connect to a custom *TCP* server that throttles the original 100 Hz frame rate delivered by the *Vicon* motion capture system to a frame rate more suitable for

the *JavaScript* application executed in the individual end device's web browsers.

3.2.2. Exploration of Interaction Techniques

The physical globe serves as an anchor in space, whose position and orientation in space the application is monitoring. It can be configured to be a passive element display of digital information and assume the role of a spherical display, as well as an active remote control for other displays showing the same dataset. The tablet application can be configured to serve as an AR lens: when holding up a tablet to the globe, digital layers are superimposed on the camera image of the globe that is displayed on the tablet screen. It can also be configured to serve as a magnifying glass: in this mode, an enhanced and enlarged virtual image of what would be seen by the camera is rendered, in relation to an imaginary focal point in front of the tablet computer. We also implemented basic gestural interaction for when the user prefers not to use a tablet as a means of interacting with the physical globe. In summary, our setup enabled us to explore the following modalities:

Tablet

- Serves as a lens onto the physical globe and reveals associated digital information (existing midterm project).
- Serves as a magnifying glass that uses the physical globe as an anchor in space, but reveals much higher-density information, the granularity and zoom level of which is adjusted by the physical relation of the objects.
- Serves as a remote control for displaying map views on the master screen.
- Serves as a selection tool for bringing detailed views onto the master screen.

Globe

- Serves as a passive control for changing views through the AR lens.

- Serves as an active master display by displaying data on its physical surface.
- Serves as a remote control or presentation tool for displaying globe views on the master screen.

Hands

- Used to control the rotation of the globe, which means controlling the coupled views on other devices when the globe is configured to be a remote control.
- Serve as pointers to the views rendered on other devices when performing a “looking glass” gesture.

Usage of the globe in its basic form can be regarded as “passive mode:” the globe itself does not change its state, but serves as an anchor point for users to select portions of a map they are interested in. They zoom in intuitively by approaching the physical object with their lens. They can select datasets on their tablets and drag them onto the camera image of the globe, which results in those visualizations becoming instantly visible through the respective user’s lens. Simultaneously, many users can get a first-person perspective on large datasets and control data position and granularity through their position in space in relation to the tangible object. Users can also chose to make a dataset publicly visible, which enables other users (who may be engaging with the physical interface or participating from remote locations) to see the same data, but from their personal angle.

However, when the globe is rotated on its axis or moved around in space it transforms to “active mode”: Since the views of individual users of the physical interface are coupled with the globe’s orientation, this action changes each of these user’s perspective and the globe essentially becomes a remote control for all lenses that are being pointed at it.

Like many traditional physical interfaces, the globe is constrained to its physical shape, which obviously reveals severe

limitations when we look at how user's interactions and the resulting views could be recorded and repeated, shared among users, or reused in remote locations. In order to overcome this limitation, we need to enable the decoupling of any given view on a user's lens. By using a marquee finger gesture, users can create an arbitrary map clipping, which is stored on their device for later retrieval and can be viewed in 2D or 3D and manipulated on-screen. This view is not tethered to the physical interface anymore and can also be shared with users in remote locations.

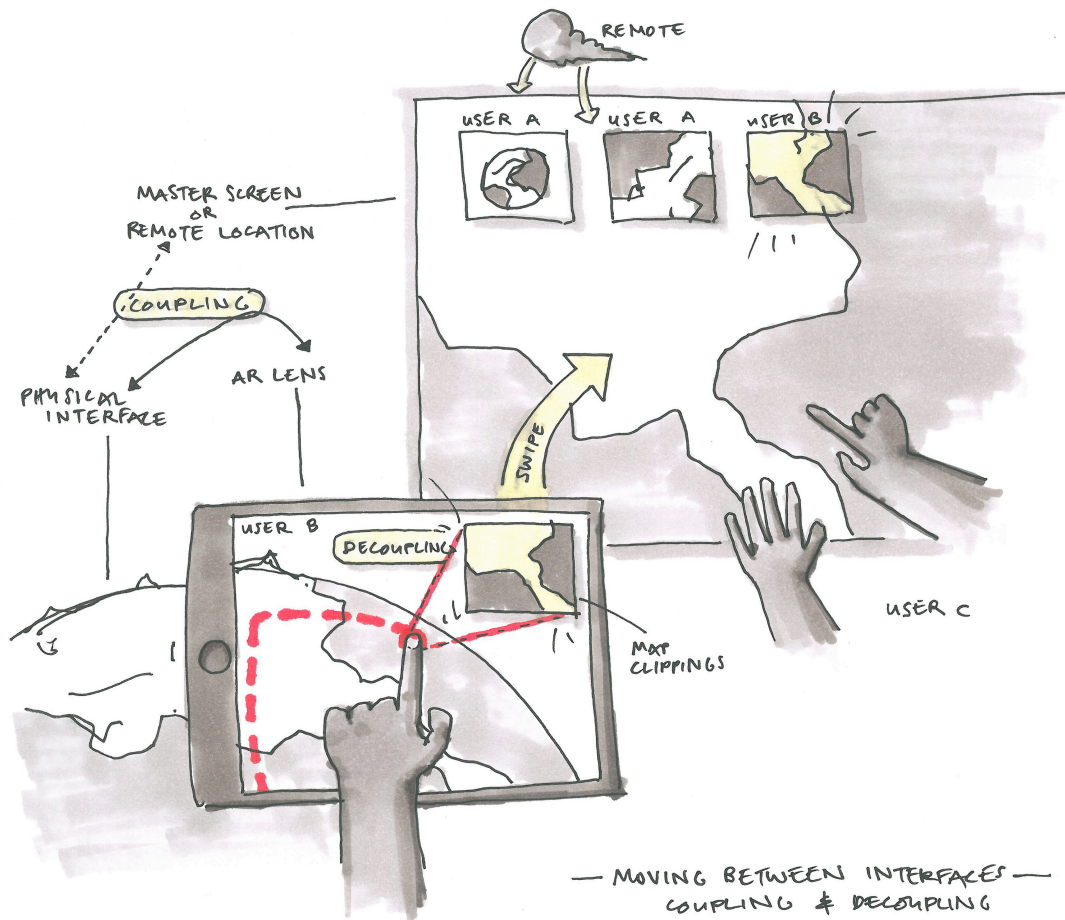


Figure 10: Coupling and decoupling of individual views

To take full advantage of this concept, our final network of interfaces also introduces a master screen, to which users can send their clippings with a simple swipe gesture. This screen could be regular desktop computer, a touchscreen or a gesture-enabled display, where other users can inspect map clippings that were created through the physical interface or by remote users. The master screen could also be directly coupled with one of the lenses and present its view to a larger audience, or it could be coupled with the globe, whereas the globe would serve as a gigantic trackball.

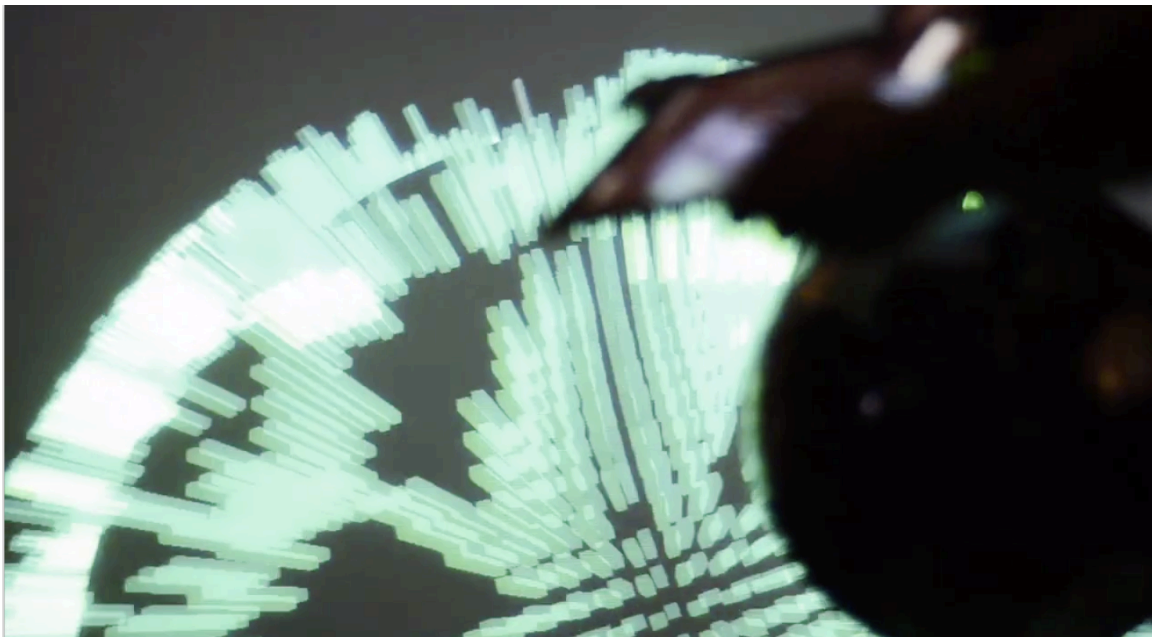


Figure 11: Using a tablet computer to physically define a larger view onto a physical globe

3.2.3. Discussion

This project presented an array of interfaces to facilitate the interaction with and presentation of geospatial datasets. It explored the globe as tangible interface that can serve as a “passive” anchor for several users at a time, and also as an “active” remote control for several users’ view on the data. During the

development of this project we also studied a concept of coupling and decoupling of any of the individual interfaces.

Not all modes of interaction were equally promising. Even though with our AR application we can quickly shift the point of focus to a different area on the virtual map by moving the device around in physical space, the resulting views on the tablet screen are essentially limited to the resolution of the map on the physical globe, which by its very nature is of a macro scale. However, when configuring the tablet as a magnifying glass, we are limited by physical jitter, similar to problems we might encounter when taking pictures with a compact camera at a very high zoom level. Gestural interaction worked well: The use of a looking glass hand gesture for enhancing large views on the master screen, while displaying visual cues about the area being enhanced on the spherical display, worked well, but was limited by the improvisational nature of the spherical display, which was merely a top-down projection onto the globe surface and exhibited distortion.

Due to time constraints, the process of reconfiguring (coupling and decoupling) individual components of the setup was not sufficiently explored. We believe that while the tablet application may not be successful at replacing a mouse-controlled graphical user interface, there is potential in an environment of many inter-connected devices with different input modalities that can be tethered and reconfigured to serve for different tasks, and the future focus should lie on how we can make this reconfiguration process as seamless as possible.

3.3. *Sublimate Terrain Model*

During work on the *Tangible/AR Browser* it became apparent that the physical constraints and fixed resolution of a globe display were impeding the usefulness of the resulting interface, and a more flexible way of physically representing terrain would be beneficial. Namely the lack of pan and zoom controls imposed by the physical object was too limiting, and it did not allow for a fine-grained look at the superimposed geospatial data.

3.3.1. Concept

These considerations were taken into account when developing the *Terrain Model with Superimposed Virtual Information*, created as part of the *Sublimate* project. Leithinger et al. had previously explored how volumetric geographies can be navigated and displayed using a shape display (Leithinger and Ishii 2010).

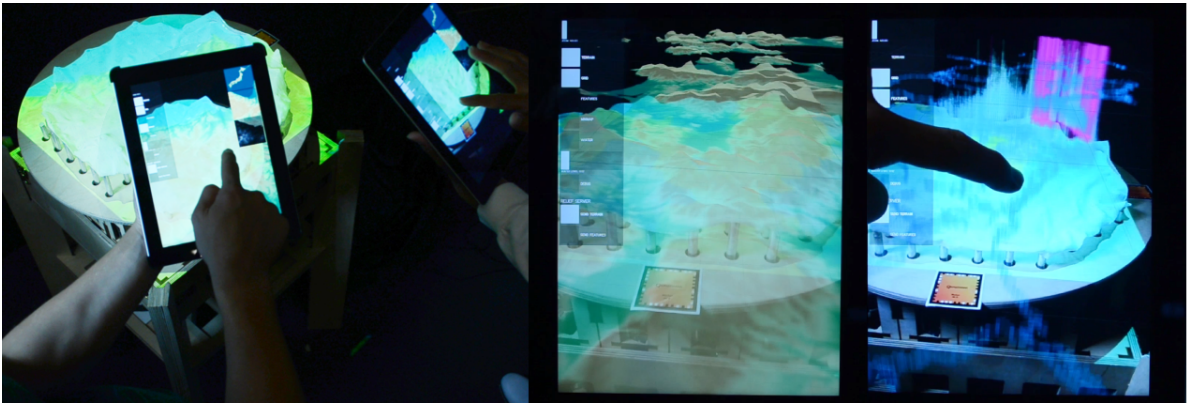


Figure 12: Sublimate Terrain application running on two iPads

The *Sublimate Terrain Model* application expands on that concept and enables multi-user navigation through the lens of tablet computers that are held up to the surface of a shape

display, which is able to physically render arbitrary sections of the digital terrain model.

When describing partially physical, partially digital rendering of data, we are referring to a recently published concept entitled *Sublimate: State-Changing Virtual and Physical Rendering To Augment Interaction with Shape Displays* (Leithinger et al. 2013). We envision that information could change states from digital (or liquid) to a physical manifestation (or a solid). In this system, data can be rendered both physically, through shape displays, and virtually through floating 3D graphics.

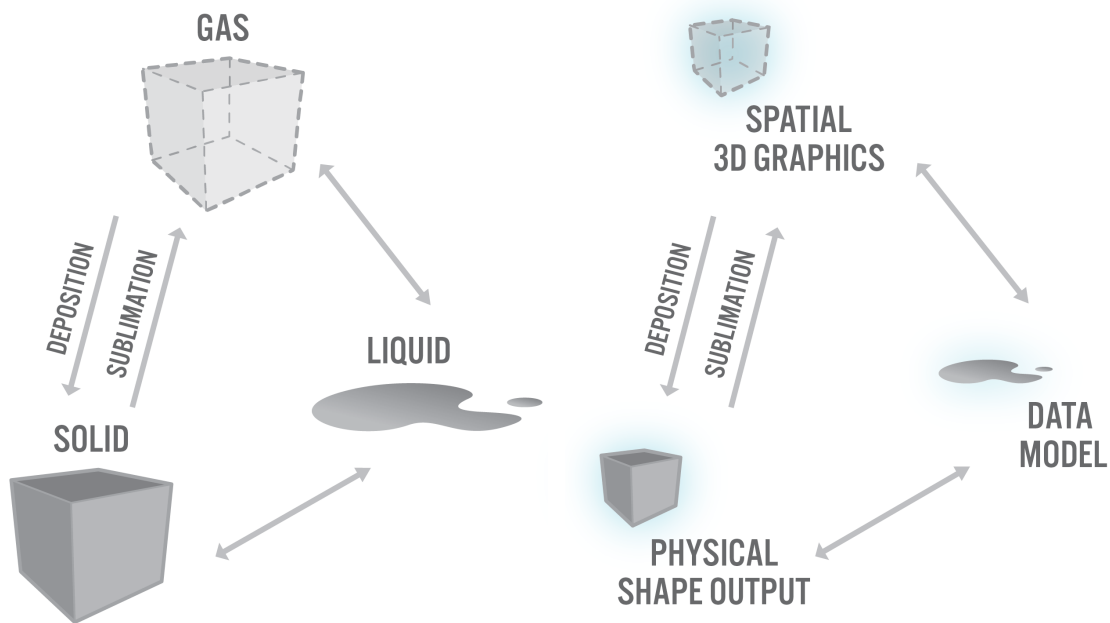


Figure 13: Sublimate concept schematic as in (Leithinger et al. 2013)

The essence of the system is the partially physical, partially digital rendering of volumetric data. Physical rendering would be achieved by programmable matter, or—more achievable on the short term, 2.5D shape displays.

Meanwhile, hovering graphics “can help to compensate some of the limitations of current generation shape displays. They en-

hance the visual resolution, size and scale of shape output, and augment features a particular type of shape display might not be able to render ...” (Leithinger et al. 2013). In other words, a holographic display hovering over the programmable physical surface would be able to render contextual data points or additional terrain information, thus eliminating the need for a user to hold up a personal lens to the physical interface.

3.3.2. Implementation

As part of a range of prototype applications exploring this concept, we built a proof-of-concept system and application that uses a 2.5D shape display to render physical terrain, while several tablet computers can be used to interact with the physical surface simultaneously.

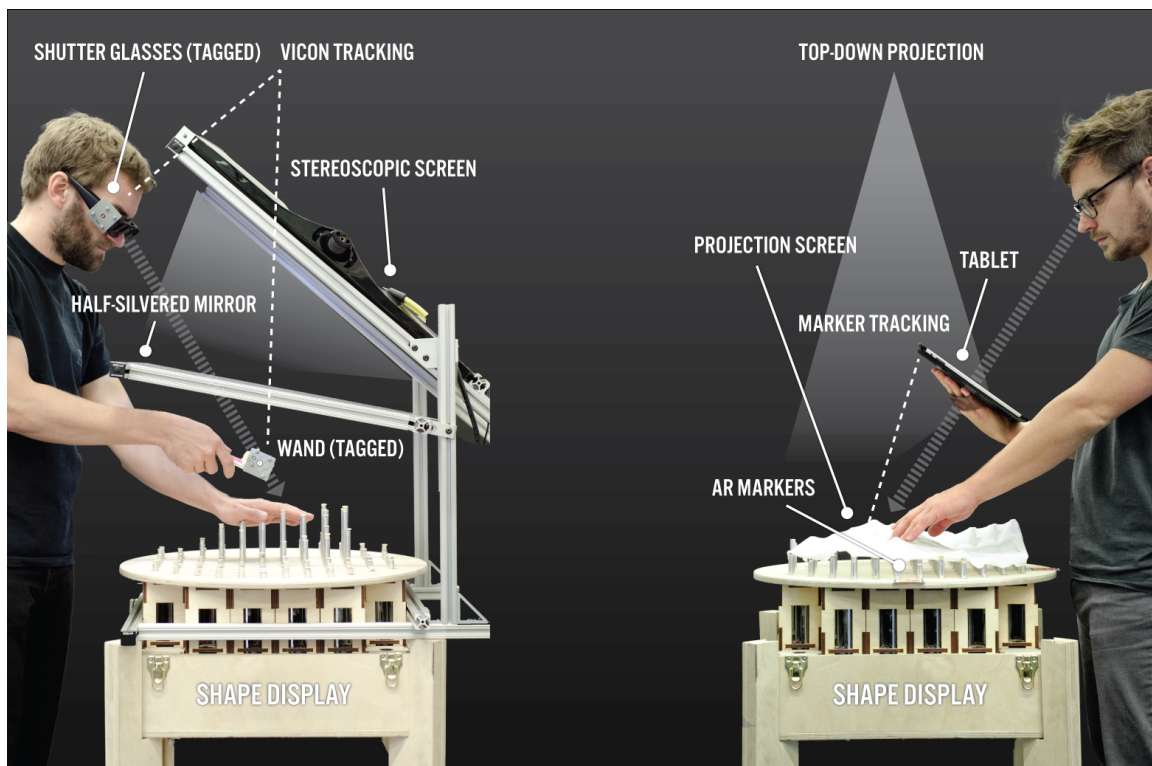


Figure 14: Systems developed for the Sublimate project

Seen through the camera of the tablets, we can expand the horizon of the physical map and display the terrain as it extends far beyond the edges of its physical manifestation.

The author implemented pan and zoom controls on the tablets to enable all users to change the region of interest. Moreover, individual users may display additional data overlays—for example, in our scenario, a map showing radioactive contamination levels in Japan—as well as control simulation parameters such as rising sea levels.

3.3.3. Implications and Discussion

Sublimate showed a new vision of *“how 3D spatial graphics and physical shape output can be combined”* (Leithinger et al. 2013), with a focus on how the transition between these states would look. Two systems were developed on top of an existing 2.5D shape display. Due to technical limitations, the system that employed a stereoscopic display can only be used by one user at a time, while the implementation that uses tablet computers enables multiple users to simultaneously control the shape display. It can provide collaborative interaction with 3D data, and extend the shape display’s resolution and scale beyond the physically represented area. The authors *“believe that the intersection between physical shape output and spatial graphics is a rich area of exploration, and that the state transitions [between physical and digital] can be a valuable avenue for further investigation.”* While requiring the user to hold a tablet computer in her hands instead of interacting with the programmable surface directly, the advantage of the latter configuration is that users can refer to the physical model during discussion with each other, while controlling a personal high-resolution view that allows them to switch between different perspectives of surrounding terrain or additional data layers.

4. Stratarium

4.1. Project Goals

The *Stratarium* project described in this chapter further explores the outlined design space at the intersection of spatial data visualization, earth science literacy, and interaction with physical terrain representations. These are the main challenges:

- **Terrain modeling** including digital elevation models (DEM) and physical rendering through a shape-display, as well as digitally fabricated physical terrain models.

Digital elevation maps of the Earth’s surface are publicly available at no cost through a number of web interfaces. These systems typically divide the planet into a grid and allow the public to download individual tiles containing raster elevation data for the selected area.

- **Sensor data acquisition**, cleaning, normalization and aggregation, and the implementation of a geospatial database interface to query the resulting datasets.

A large number of geospatial data is available in a multitude of formats and from many different sources, such as government agencies, private organizations and individuals. We can differentiate between data that originates from high-end sensor networks (such as satellites), or “*Volunteered Geographic Information*” (Meng 2010), i.e. data that is collected and added to databases by individuals, for instance with hand-held sensor devices.

- Combining the above in **interactive systems** that allow users to “drill down”, both literally—by reaching underlying terrain levels, or strata—and metaphorically, to support analysis and enable knowledge building. Such systems will need to address the perceptual challenge of combining partially physical rep-

resentations and overlaid graphics through actuation and projection mapping. We need to determine which aspects of the scenario need to be materialized and under what conditions – which aspects do we render virtually, and how do we transition between the individual information layers?

In User Interface design, “drilling down” means to transition from a layout presenting an information overview to more detailed branches (Irani and Li 2005) – or semantically, to go from a broad concept to specific aspects of the topic. A drill-down structure enables us to structure complex information hierarchically, so we can perceptually manage it as a whole and study its more expansive areas separately. If we translate this metaphor to a physical object, for instance a stereo, we could compare this concept to the process to taking the stereo apart, separating its layers, and studying its individual components and the function of its intricate circuits in isolation. Multi-layered tangible models that we can take apart also have a long history when it comes to studying biological objects that we usually can’t see, such as our inner organs.

Likewise, if an object is too large to be studied in its physical entirety—such as our planet—we often create tangible miniatures that allow us to explore specific aspects of the whole. Digital maps and data visualizations are a flexible and efficient form of organizing information about the world at multiple levels of granularity, but they exhibit the weaknesses of mere data visualization, in that data needs to be contextualized to be fully understood and enable intervention and response (Indreboe and Puig 2012).

Moreover, on-screen information displays lack the advantages of tangible interfaces (Ishii and Ullmer 1997) and limit our perceptual bandwidth to that of our eyes. The dream behind the application prototypes described below would be an “*Ultimate Display*” (Sutherland 1965) that can produce a manifes-

tation of the most remote corners of this planet and is connected to a worldwide sensor network, a “dashboard of the Earth”, a tool for policymakers and educators alike that allows us make informed decisions for the future.

4.2. Project Background

Stratarium is based on the premise that with a hypothetical future material “*that can change form and appearance dynamically*” (Ishii et al. 2012) we would be able to convert a digital elevation model (DEM) of arbitrary places on the planet to a high-resolution, multi-layer physical model, on top of which we could render and interact with graphical elements such that “*floating graphics augment physical objects*” (Leithinger et al. 2013).

There is a long tradition of passive tangibles that organize information in layers and allow us to construct knowledge by taking apart physical objects. Especially for objects whose inner systems are usually invisible—such as the human body—tangible models that we can take apart or “explode” are essential in helping us understand individual components of the system—such as the human heart—and how they are functionally connected. Similarly, in the case of an object whose scale is too large and exceeds our spatial understanding—for instance a building, a slice through terrain or our planet as a whole—we traditionally create tangible models. However, these tangible objects, for all their instructiveness, are unable to visualize dynamic processes such as blood flow in the case of the human heart, or the movement of tectonic plates in the case of planet Earth. Due to the static nature of passive tangibles we usually resort to graphical animation on 2D screens to visualize such processes. It is precisely this intersection of materiality and graphics that *Sublimate* is addressing, and we believe that combining physical shape output and overlaid, or “floating” graphics pose a unique advantage when exploring 3D da-

ta, allow for novel and engaging interactions, and present a rich area of exploration (Leithinger et al. 2013).

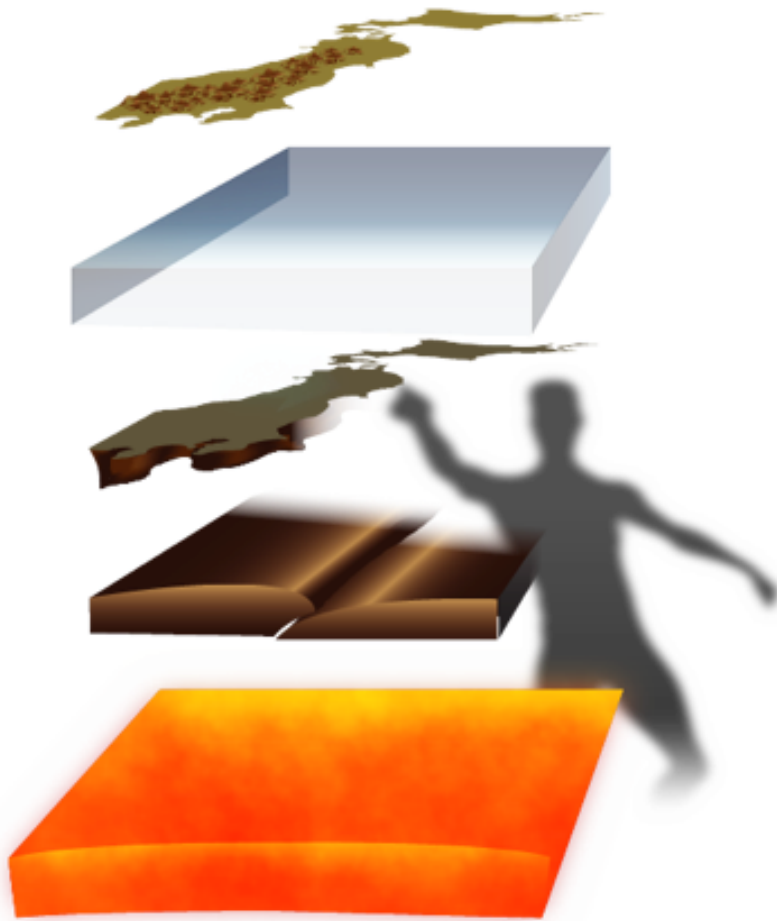


Figure 15: Idealized version of a “world dashboard” with physically rendered strata

The ideal version of the system we are trying to approximate would provide interactive visualization, or “*steerable simulation*” in a tangible, immersive and multi-sensory environment to enable our heightened understanding of the observed phenomena, and allow for “*multimodal manipulation and perception of abstract information*” (Chen 2005). Spatial metaphors in virtual worlds can “*enhance the meaningfulness of data and provide qualitative insights*” (Erickson 1993)—but if the “*Ulti-*

mate Display” (Sutherland 1965) were to become a reality we could combine our spatial data collections with physical models whose layers we can explode and take apart, so that we can reveal their inner structure and the underlying layers of information, as well as the connections and interdependency of natural systems.

4.3. Application Concept

4.3.1. Themes

The National Science Foundation has outlined a range of concepts of Earth science that should be known to the public at large as part of its *Earth Science Literacy Initiative*. It defines Earth science literacy as “*an understanding of Earth’s influence on you and of your influence on Earth.*” Among other goals, the Earth-science-literate person “*understands the fundamental concepts of Earth’s many systems [and] is able to make informed and responsible decisions regarding Earth and its resources*” (NSF 2010). Titled “*Big Ideas*”, the report contains a multitude of concepts, including “*8.7 Humans cannot eliminate natural hazards, but can engage in activities that reduce their impacts ...*”, or “*4.5 many active geologic processes occur at plate boundaries.*” These ideas form the conceptual basis of the *Stratarium* application.

To create a meaningful application scenario that would visualize specific aspects of the subject matter based on design principles established by the *Sublimate* vision, we limited the scope to only show terrain data and contextual information of the specific geological situation around Japan. The terrain is integrated with a historical record of earthquakes and the simulation of stress in the subduction zone to the east of Japan. In this area, the Pacific plate is pushed underneath the overriding plate that Japan’s main island sits on top of. The two plates constantly grind against each other, and enormous

forces build up in layers of the overriding plate, which regularly ruptures in certain places, thus displacing matter as well as lifting the ocean waters above, which results in the flood waves known as Tsunamis. These waves travel across the ocean's surface in all directions until they hit land, and they can have devastating effects on coastal communities. The goal of this first application prototype is to provide an informal learning experience that enables a user's understanding of this situation through interaction with observed data, as well as simulated, interactive visualizations of this causality chain.

Informal learning, as opposed to education that takes place in a classroom, can play an important role in creating an informed public. A report by the National Research Council identifies several strands of informal learning. Learners can, for example, *"experience excitement, interest, and motivation to learn about phenomena in the natural and physical world"* or *"manipulate, test, explore, predict, question, observe, and make sense of the natural and physical world"* (Bell et al. 2009). Based on these premises we devised a system that essentially constitutes a *"Designed Environment"*, or tangible Earth science lab, that enables novice users to explore and engage with geospatial data and the aforementioned natural phenomena in a non-linear, unguided fashion.

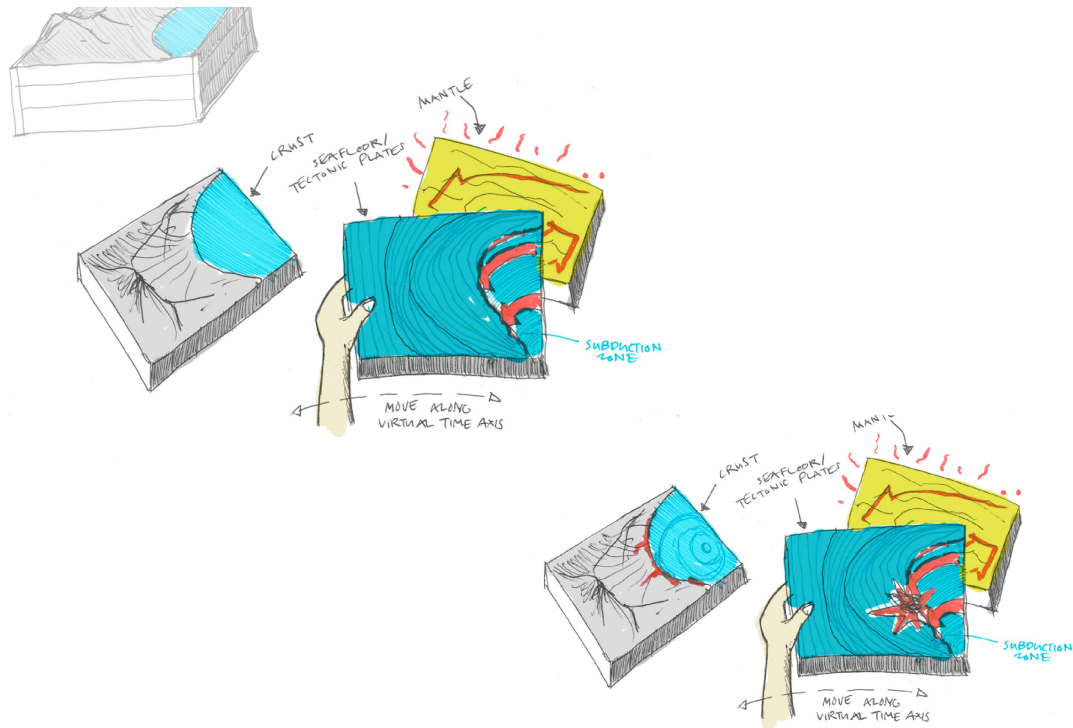


Figure 16: Storyboard for Tangible Earth Science Lab A – Earthquake in a subduction zone and resulting Tsunami

4.3.2. Setting

The resulting *Stratarium* application is an iteration of the software created for the *Sublimate* project. It allows users to interact with the phenomena observed in the real world on top of a physical terrain model. However, instead of focusing on surface-only data exploration we are able to “explode” the strata of the physical representation. Instead of having only one physical representation (relief) on a table-top that corresponds to a digital data model (map) that we can pan around in, we are able to navigate vertically through the several suspended, stackable physical layers that comprise the upper portions of the planet, and augment the physical layers graphically. Through gestural interaction we are able to actuate those layers and to “drill down” from the surface and materialize the ocean floor and the earth mantle. Here we can

experience the immense energy that builds up where the tectonic plates grind against each other. We can also witness how they rupture and release this energy, and we can witness continental drift. We are then able to navigate back to the surface and see how this kinetic energy is converted into a flood wave like the one that hit the mainland of Japan in 2011, causing a cascade of events, which ultimately resulted in the radioactive contamination we can observe today. As opposed to a static physical model, we are able to experience the causality chains and underlying models that led to the collections of measured data that our system is displaying through partially physical, partially digital rendering.

4.3.3. System Design

Our *Sublimate*-style interactive system needs to integrate interaction with physical representations (terrain) and co-located graphics (geospatial data layers and visual effects).

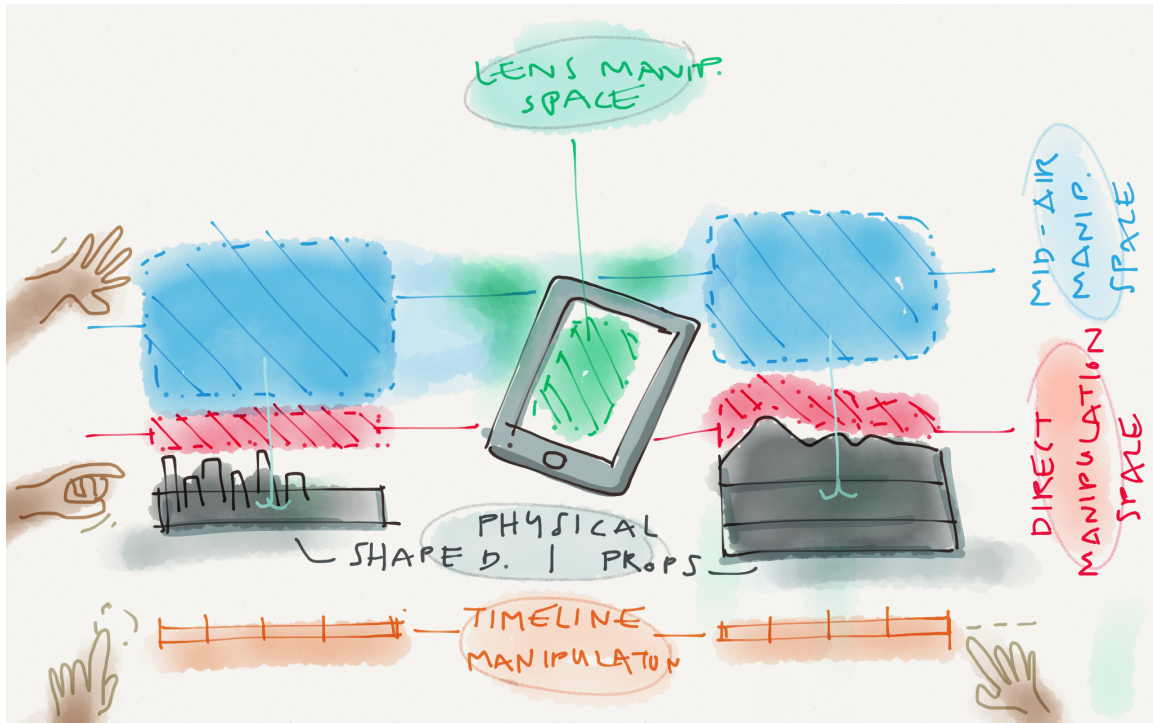


Figure 17: Combining physical representation and hovering graphics as in *Sublimate Terrain Model* (left) and *Stratarium* (right)

Ideally, the system should support direct tangible interaction with the physical props. The physical layers are augmented graphically, hence their position and orientation in physical space needs to be sensed and recreated in virtual space so that we can project graphics onto their surface.

The system also provides a mid-air interaction space where the virtually rendered data is situated. In addition to spatial navigation, we need to be able to navigate temporally and explore the applicable data layers as they change over time.

Optionally, we should be able to interact with the system through tablet computers, which can add a graphical user interface for greater flexibility.

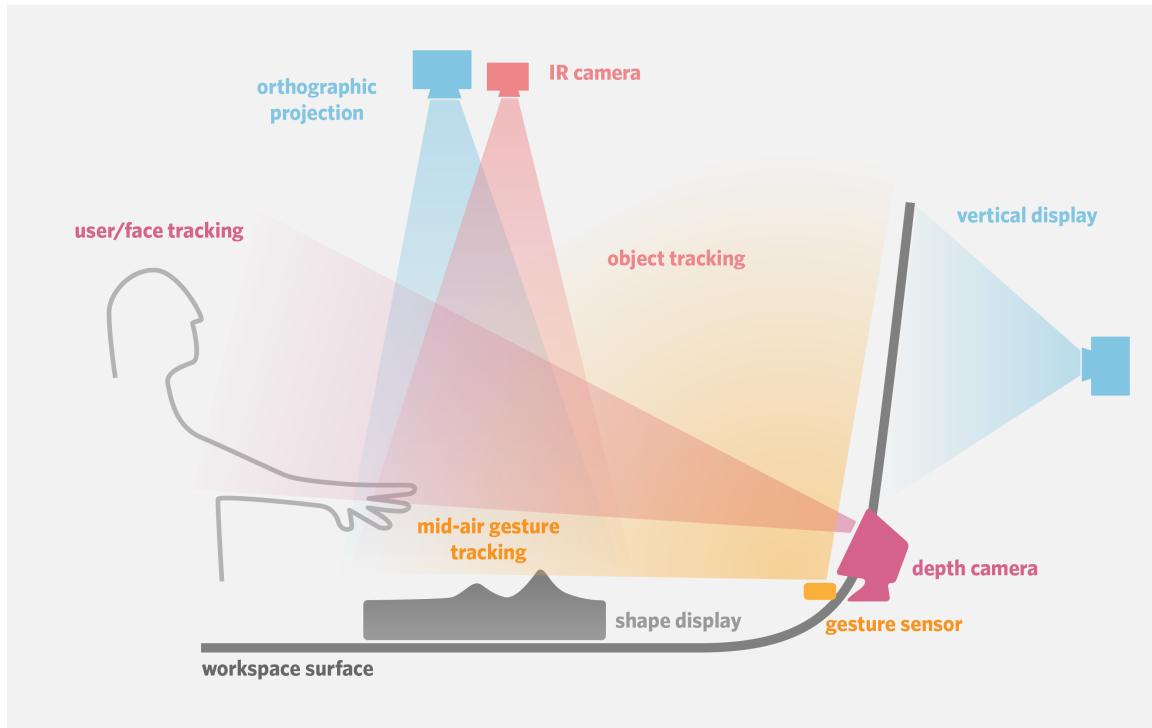


Figure 18: Integration of sensing hardware for the Stratarium system

For graphical output, our system includes two projectors (or one ceiling-mounted projector and one vertical screen). The vertical screen provides space for context information as well as vertical section cuts of spatial layers that are lying on the horizontal workspace surface. The top-down projection is calibrated with a camera, which through computer vision traces the position and orientation of our physical layers, so that the projector can display graphical augmentation on top of the physical layers.

Mid-air hand gestures are sensed using a *Leap Motion Controller*, which is situated near the back of the workspace and offers

high-resolution finger and palm tracking up to a distance of about 2 feet, which covers our work area.

The system would ideally be aware of the number of users that are currently engaging with it, and track their faces as well as recognize their head pose and thus infer the direction of their gaze. We could then identify the current region of interest, and co-locate contextual information where the user is currently looking. Head pose tracking can be achieved with a Kinect depth sensor and a database of head poses as implemented by a team of researchers at ETH Zurich (Fanelli et al. 2011).

4.4. Demo Implementation

For demonstration during the Spring 2013 member meeting at the MIT Media Lab, we implemented the parts of the system mentioned above that we identified as the most crucial to communicate the given Earth science scenario: a two-layer, stackable model of the Earth crust and the ocean floor was milled out of Polyurethane foam and served as tangible projection screen—props that symbolically replaced shape displays that would also be augmented graphically, but could render arbitrary sections of terrain or other data. Since these objects are passive and do not have any sensing capabilities, direct physical interaction is currently limited to the disassembly of the two layers. Gestural interaction is possible in mid-air through the *Leap Motion Controller*. With a circular gesture, the user is able to wind the timeline forward and backward. With mid-air swipe gestures, different thematic sections of the application scenario can be brought into focus. For instance, we can move from a view that displays Earthquake history to another view that displays slices through the subduction zone where most of these earthquakes typically occur. The application can load a variety of geospatial geometries, and it includes a wave ripple simulation and 2D bitmap terrain overlays, for instance to display vertical section cuts.

4.4.1. Physical Terrain Models

The surface elevation data we use to create physical terrain models, as well as graphical terrain meshes, is part of the *Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 2*. The *DEM* is available at a resolution of up to 30m (NASA 2011) in the form of a *GeoTIFF* grayscale height map images. Using Geographic Information System (GIS) software it can then be re-projected and processed into different resolutions and graphical representations

to form the basis of three-dimensional, real-time renderings used an interactive map system.

Similar data is available for the seafloor. To generate a three-dimensional model of the world below sea level, the *ETOPO1* dataset was used which “*represents gridded (2 minute by 2 minute) elevation and bathymetry for the world*” (ESRI 2004).

The original terrain data was available in GeoTIFF format, which can be converted to a simple grayscale height map in another image format such as PNG. Using a custom Python script, the height maps of the Earth crust and the ocean floor were converted into STL files, which describe the surface geometry of the layers. Using a CNC machine with a quarter-inch endmill we then machined this surface out of a block of polyurethane foam.

The same height maps also formed the basis of the digital terrain rendering. Using each pixel’s brightness as z-coordinate (elevation), we construct a mesh object that is composed of triangles. We also calculate the surface normal for each vertex, which are essentially the average vector perpendicular to the surrounding faces. Finally the mesh is converted into a Vertex Buffer Object, which allows us to render several layers of terrain comprised of a large number of vertices as texture-mapped, lit and shaded graphical representations.

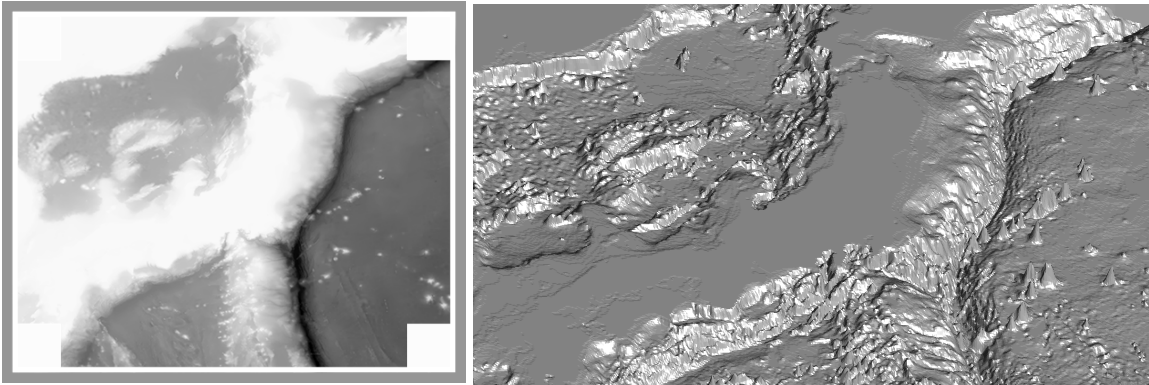


Figure 19: Digital elevation model (DEM), left; and resulting surface geometry file for CNC machining

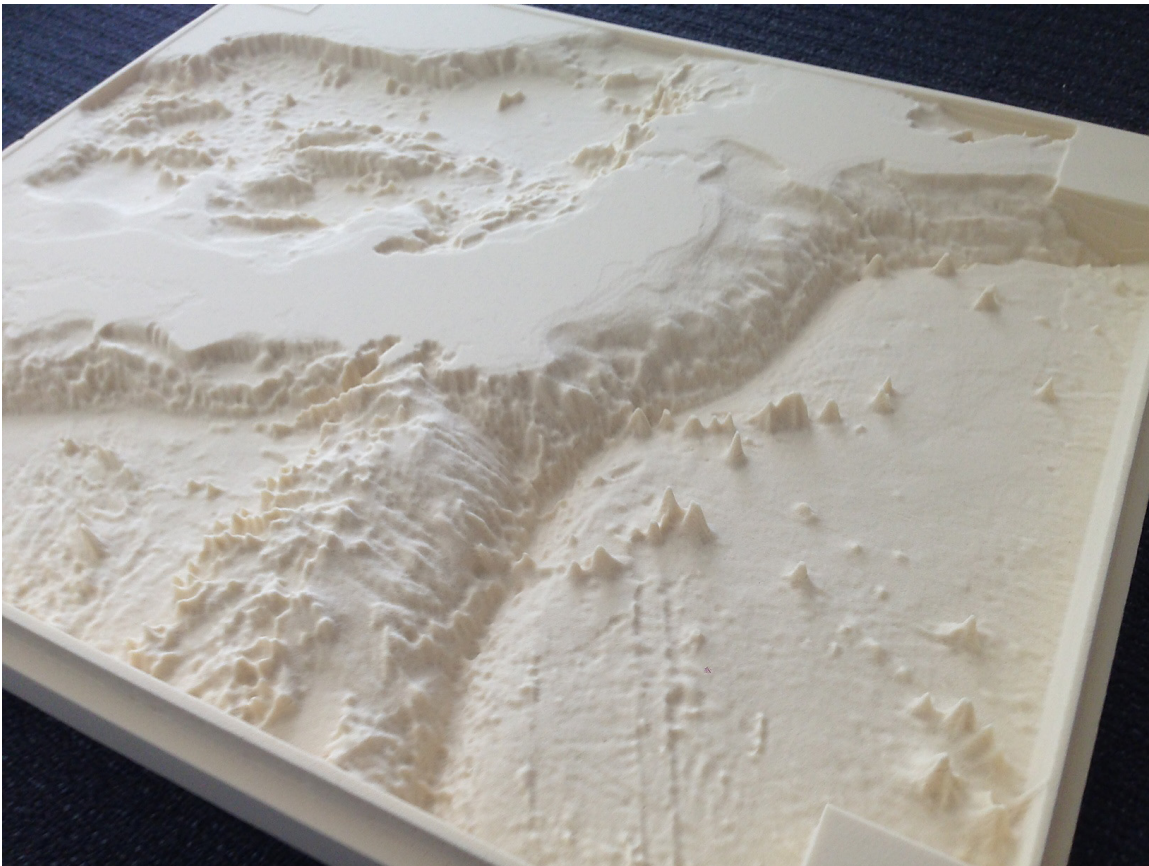


Figure 20: Terrain model created with a CNC machine, displaying the seafloor around Japan modeled from ETOPO2 data

4.4.2. Digital Rendering of Datasets

A multitude of raster, as well as vector datasets are available for public download in a variety of data formats geospatial portals, which can be thought of as the “*hubs’ or ‘geoinformation resource supermarkets’ in the Spatial Web*” (OGC). Some of these formats are binary and proprietary, but in recent years a number of open, clear-text formats have gained popularity. Based on GeoSense, we built a set of tools to aggregate and convert the source files to GeoJSON, a lightweight “*geospatial data interchange format based on JavaScript Object Notation*” (Butler et al. 2008).

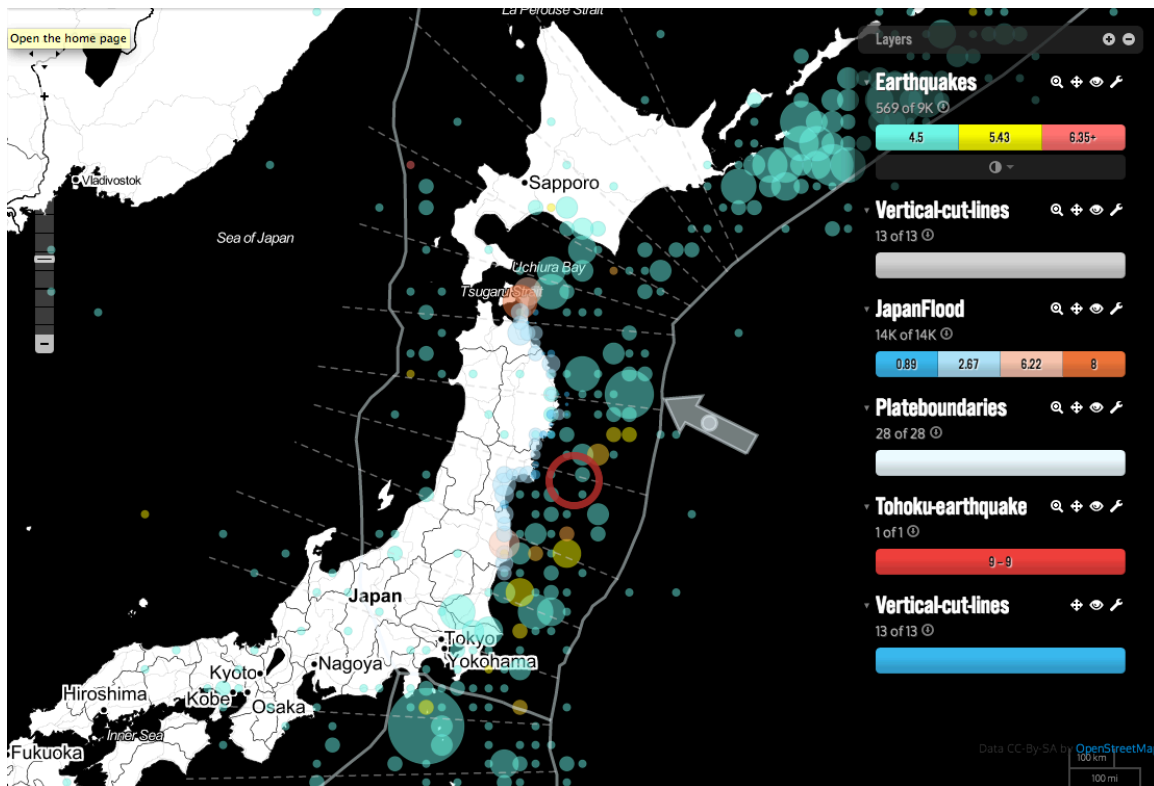


Figure 21: Geospatial data that is later loaded into Stratarium as seen in GeoSense

The resulting files essentially contain information that describes the geometry of objects in space (e.g. the polygons that make up a building’s footprint), as well as a set of arbitrary

properties for each object (e.g. the names and years of construction of buildings).

We built a C++ program that can load *GeoJSON* files and convert them into OpenGL meshes, which allows *Stratarium* to not only display and enable interaction with specific datasets that were specifically tailored to the application, but to access arbitrary collections from a variety of on-line “*resource supermarkets*”, provided they also support the format—for instance, live earthquake alerts feeds as provided by the *U.S. Geological Survey* website (USGS). This essentially connects the application to a wealth of data from the “*Spatial Web*”—bringing us one step closer to the “Earth dashboard” as outlined above.

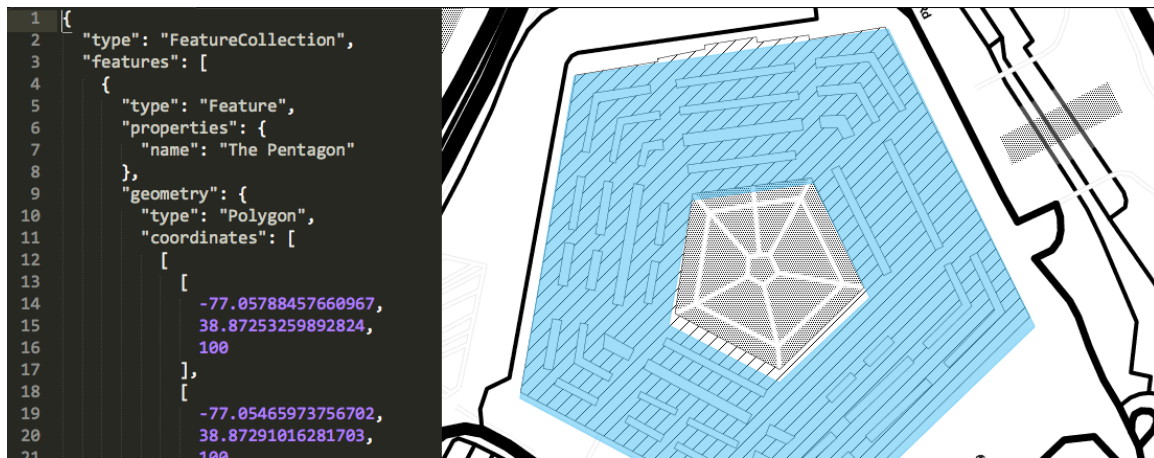


Figure 22: Example of a GeoJSON file describing geometry (left), and a rendering of that geometry (blue)

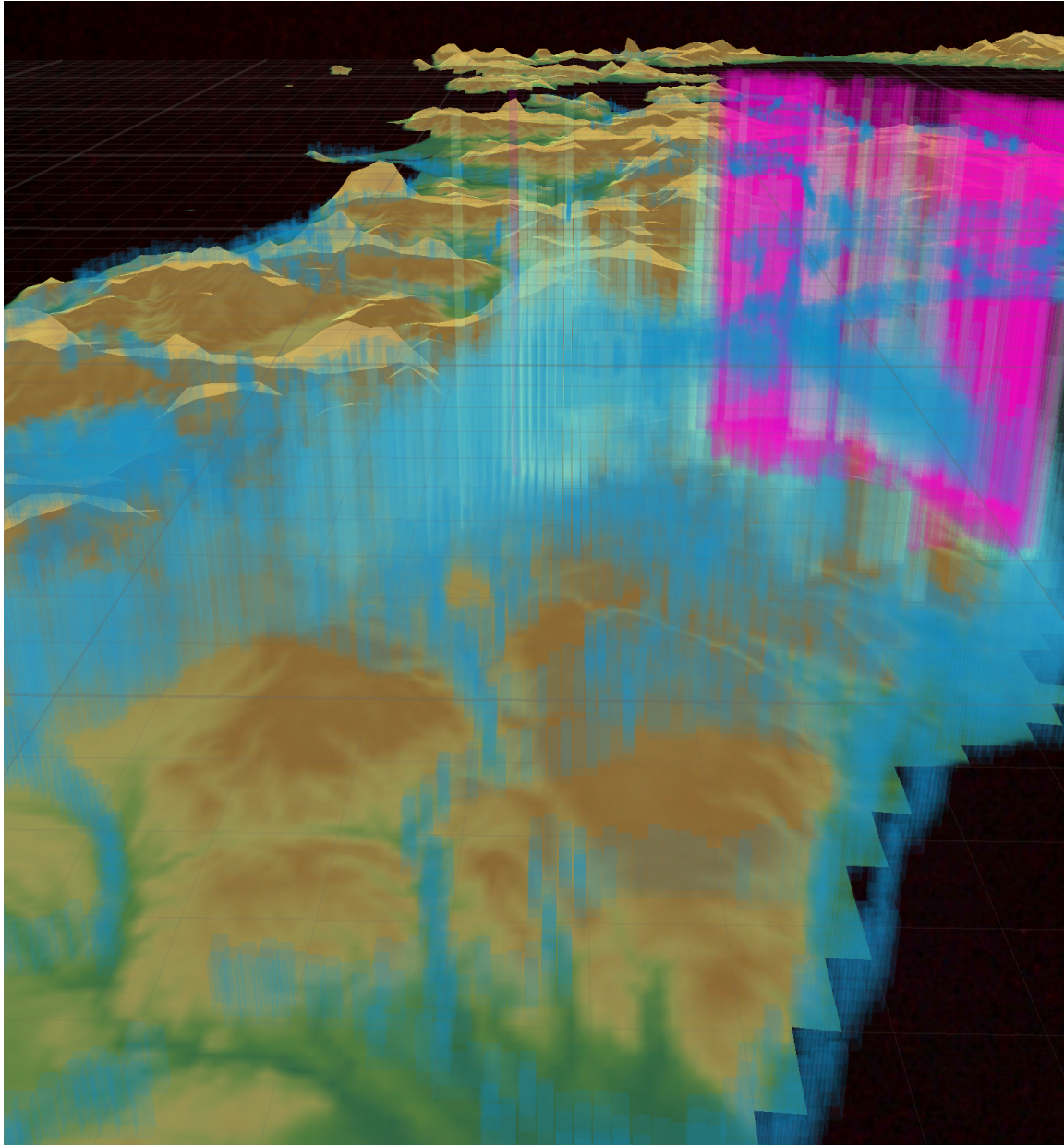


Figure 23: OpenGL rendering of textured terrain mesh from height map combined with geospatial data mesh from GeoJSON file

4.4.3. User experience

The following picture series gives an overview of the application scenario. Pictures were taken of the actually implemented prototype. Parts of the graphical representations are added symbolically to demonstrate the flow of interaction.

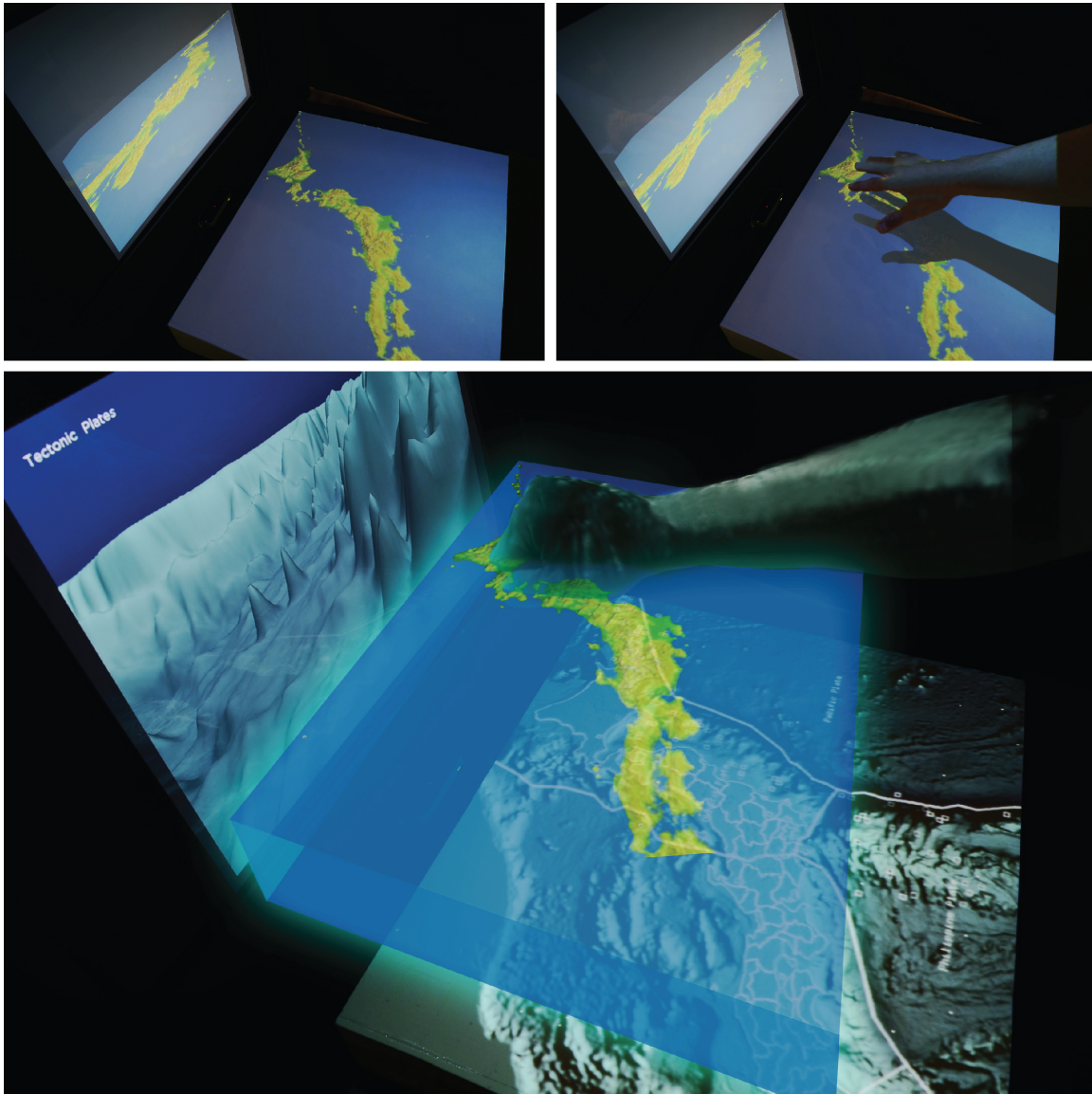


Figure 24: User experience mockup #1—lifting vertical strata to reveal underlying terrain (hovering graphics added symbolically)

When standing in front of the system, users will first be presented with a physical representation of the Japanese islands lying in the horizontal surface in front of them, and a vertical screen for a view from a different perspective. Their fingers and palms are tracked in mid-air above the physical display,

and using a simple gesture they are able to grab the visible stratum—in this situation, the Earth’s crust and the surrounding ocean waters—and pull them upwards to reveal the underlying terrain. As the top layer is “vaporized”, we can see the ocean floor and the fault line where one tectonic plate drifts towards an overriding plate and is pushed downwards.

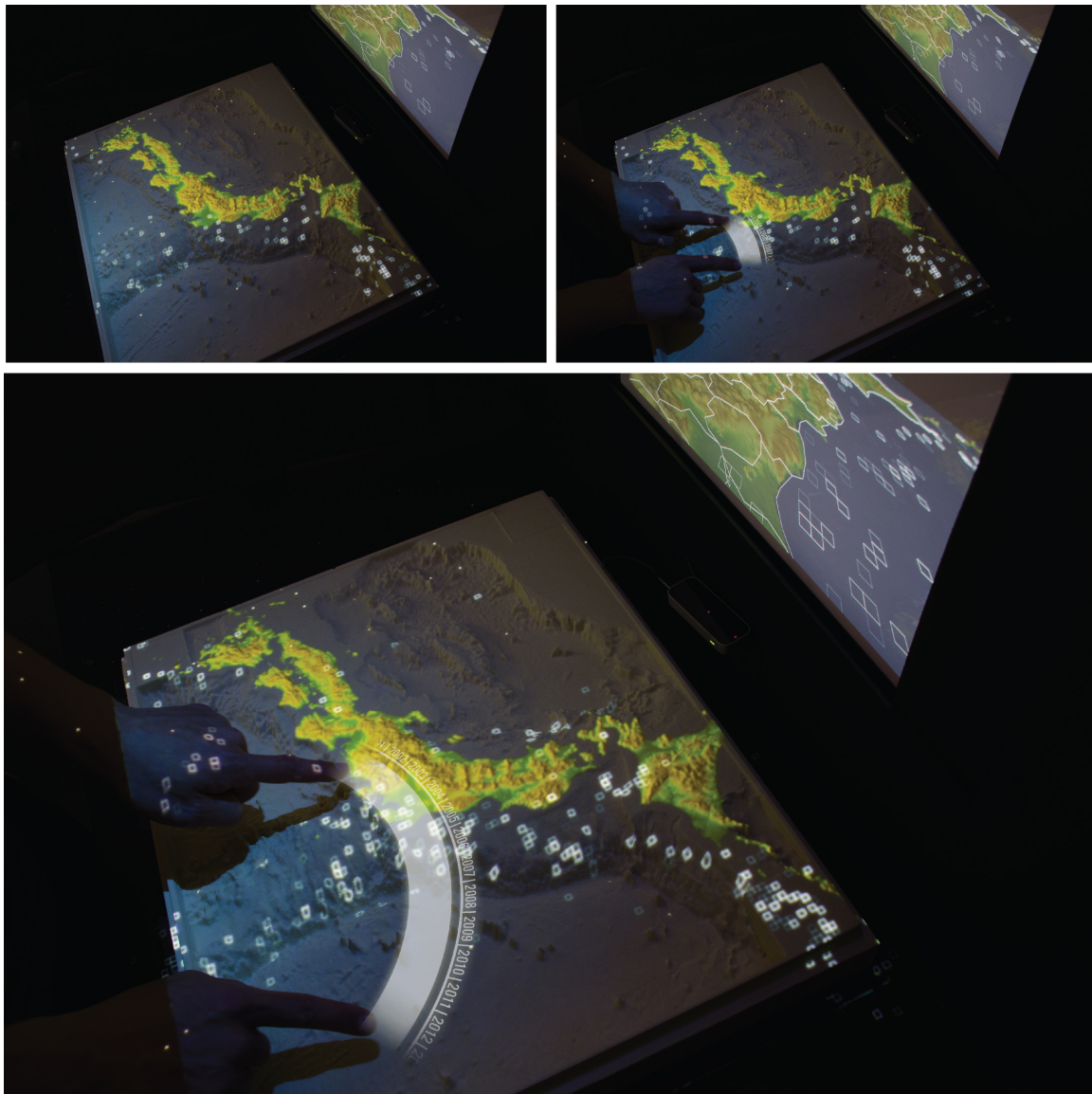


Figure 25: User experience mockup #2—displaying a datasets on the model, and browsing it over time using a circular gesture (hovering graphics added symbolically)

Users can now load geospatial datasets onto the model. In this scene, we see a historic record of earthquakes. Using a circular gesture, we can show the geographic distribution of earthquakes during the following years. We realize that they are not

distributed randomly, but seem to occur most frequently in a narrow area along the west coast of the country.

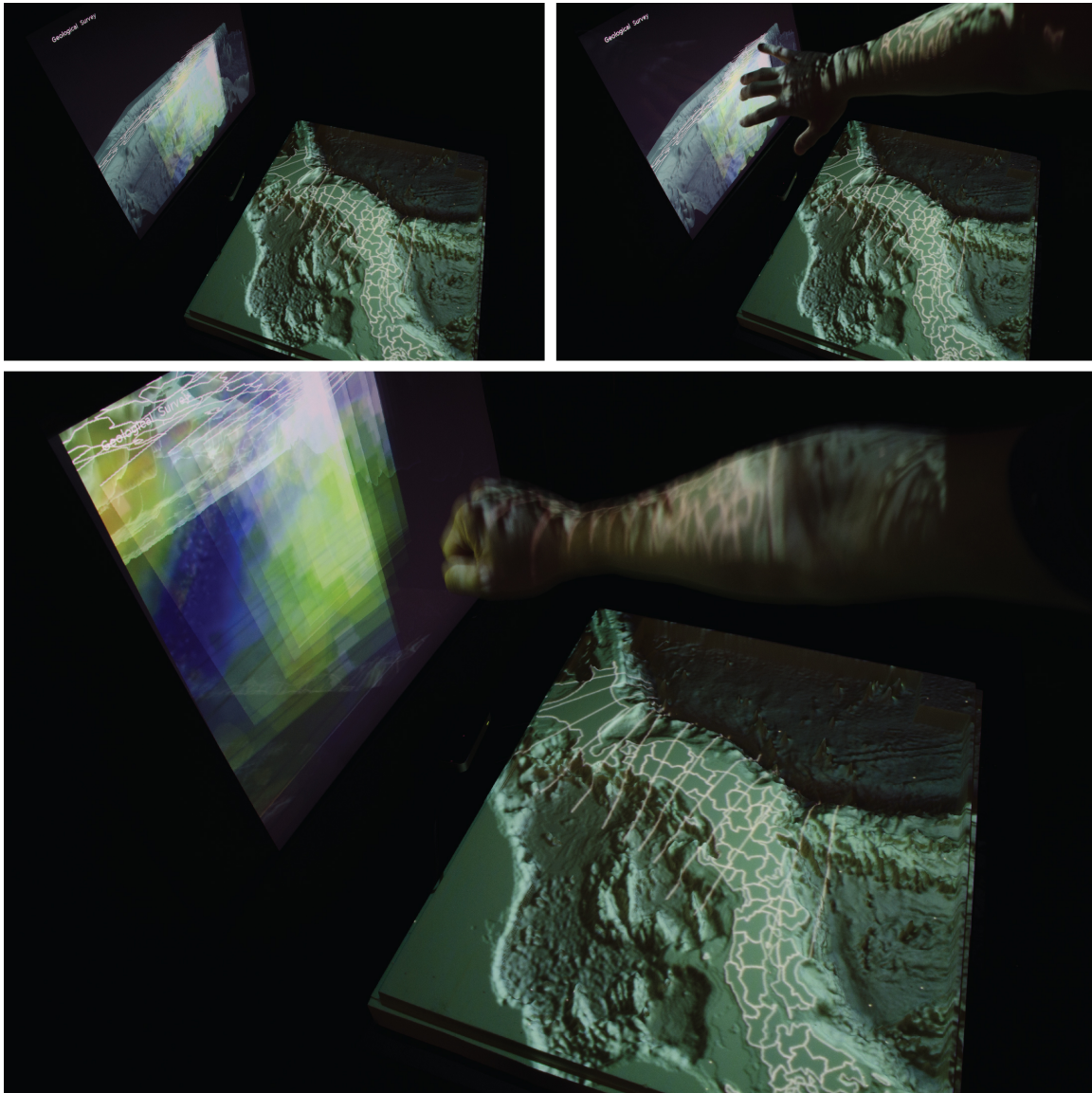


Figure 26: User experience mockup #3—using a grab gesture to navigate vertical section cuts through the terrain (actual implementation depicted)

On the vertical screen, which is perpendicular to the physical object, we can now examine a collection of section cuts through the terrain. The slices are the result of a geological

survey and allow us to study the composition of the strata, and the topology of matter in the subduction zone, where one tectonic plate is pushed underneath the other. We can grab the vertical slices and navigate through them using hand gestures.

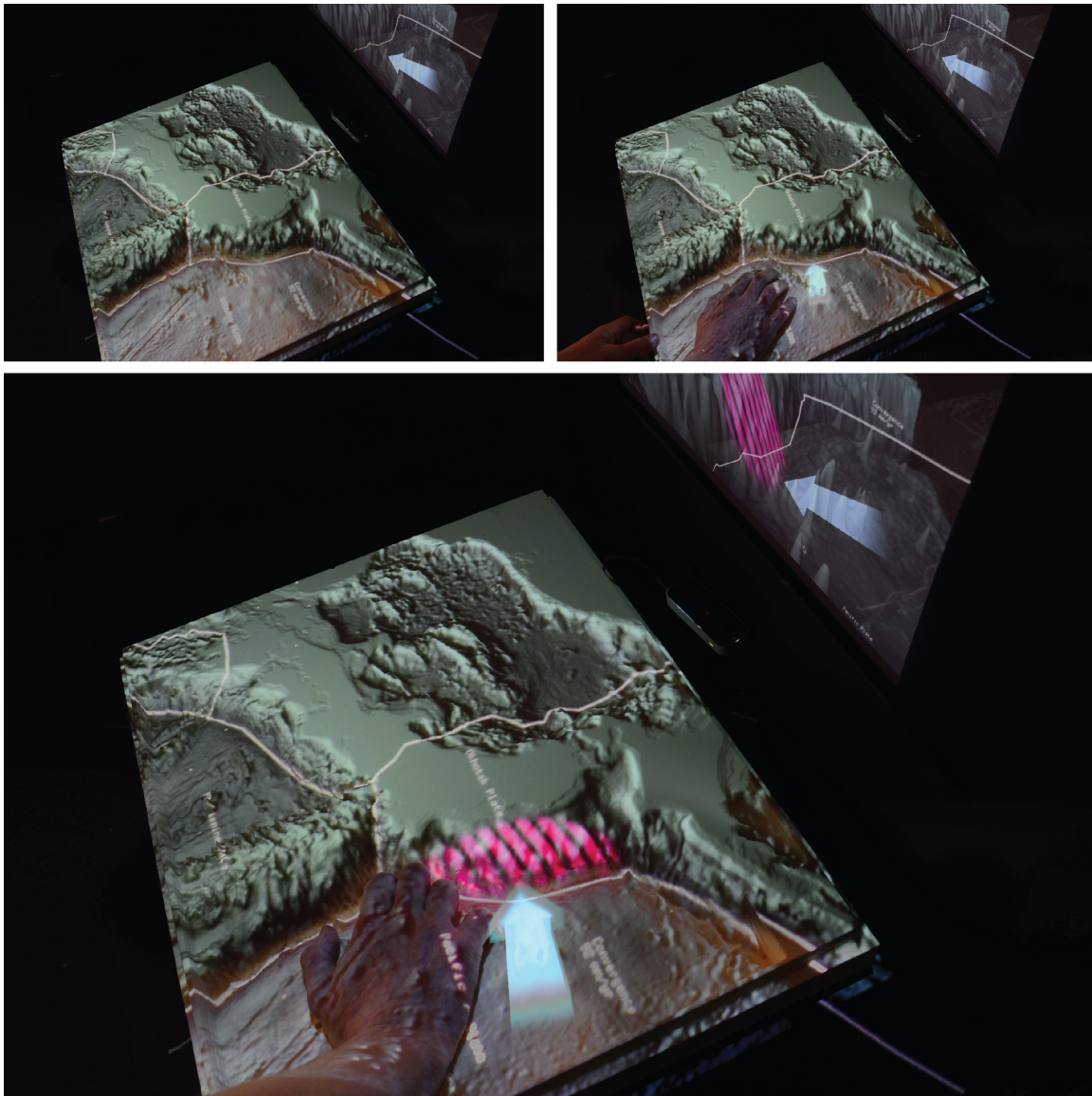


Figure 27: User experience mockup #4—using manual pressure to increase tension in the overriding plate (symbolical gesture; actual physical layers are not pressure sensitive)

Where the Pacific plate—which drifts eastwards—meets the overriding plate and is pushed down into the half-molten Earth mantle, enormous forces build up over the years. Stress accumulates along the Japanese coast, which is the reason for the large number of earthquakes we were able to observe in an

earlier step. Using a hand gesture, users can push the Pacific plate towards the subduction zone and experience the resulting stress, which is visualized graphically.

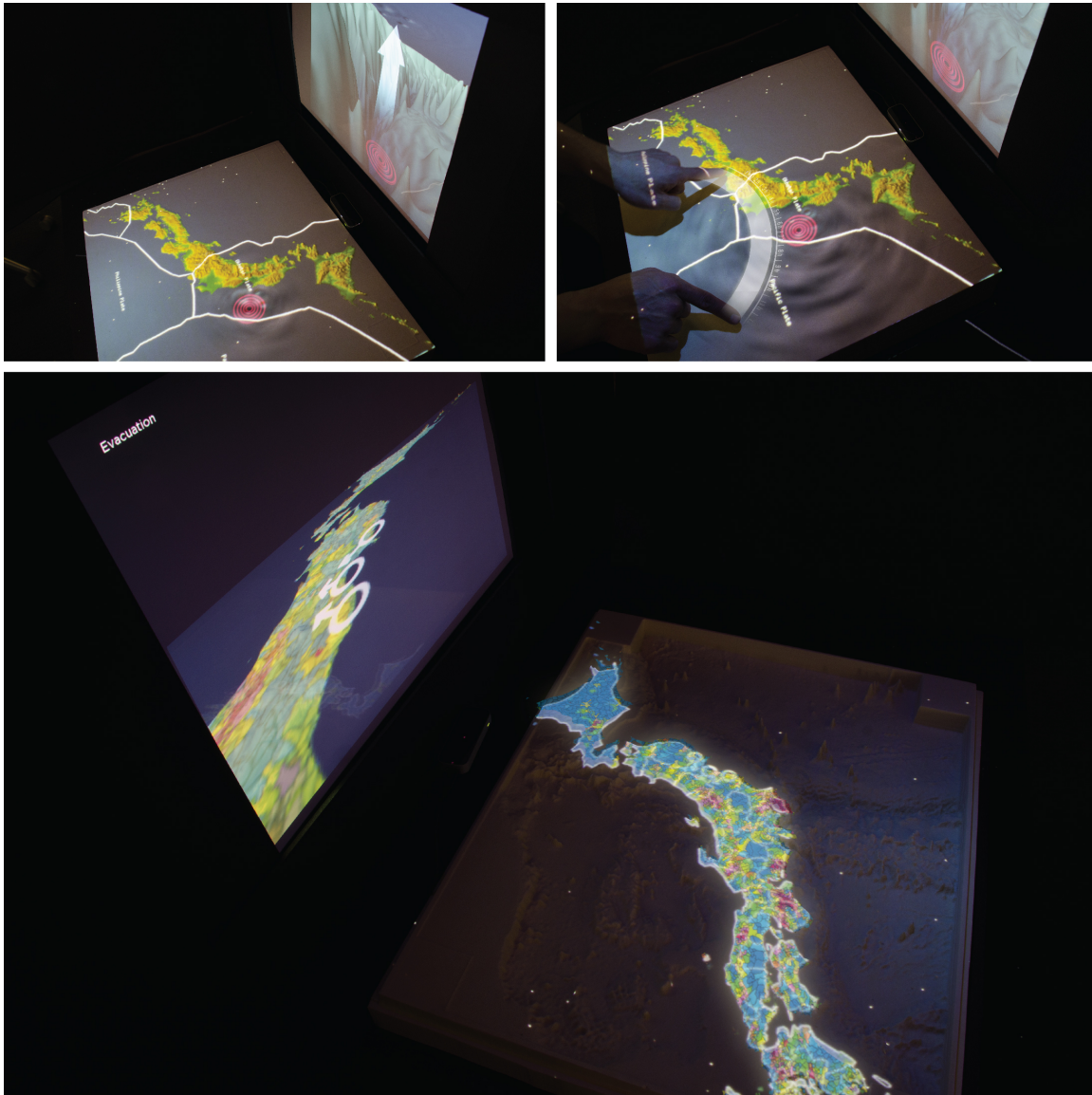


Figure 28: User experience mockup #5: tsunami wave simulation and evacuation plan (hovering graphics added symbolically)

As the tension in the overriding plate becomes too strong, it ruptures, thus displacing matter and pushing the ocean waters

above upwards. The resulting wave travels towards the mainland, and we are able to simulate its trajectory over time using the timeline gesture. Unfortunately it will hit the mainland and inundate large parts of the coast. The last frame shows a graphical overlay of population density along the coastline, and possible evacuation routes in the most affected areas.

4.5. Discussion and Future Work

4.5.1. Member Meeting Demo

The application scenario was demonstrated to visitors during the 2013 Member Meeting at the MIT Media Lab. Extensive discussion with visitors from the Japanese engineering consultancy firm *KKE*—a company with expertise in the areas of risk assessment and disaster simulation—yielded interesting pointers for future directions.



Figure 29: Author (right) with visitors from a Media Lab member company

The possibility of adding an actual mathematical simulation of shock waves to the scenario was discussed, as well as the integration of additional data layers showing areas at risk, which

are made available by the Japanese government. Other members of the community also expressed interest to implement similar application scenarios in related fields, with similar intent of equipping individuals with “*tools to better understand relationships between ecological processes, human lifestyle choices and climate change adaptation*” (Tidmarsh).

On a technical level, replacing the static physical layers—which, in the current implementation, are used as passive projection surfaces—with actual shape displays would vastly expand the application spectrum. Being able to render arbitrary geometry on the physical layers would enable us to implement more complex application scenarios that would allow us to actually experience the physical stress and the forces at work before and during earthquake events.

While in the existing application we only look at earthquakes in a subduction zone, there are other geologic situations that we could simulate with physical rendering and overlaid graphics, paired with direct manipulation and gestural interaction, thus taking full advantage of a *Sublimate*-style interface.

Figure 30 shows one possible scenario for an earthquake-prone region along a natural fault line between two tectonic plates. The user first constructs a physical structure, such as a fence, on the surface above the endangered zone. Subsequently, the system renders virtual “deformation handles” on top of the structure, inviting the user to exert a force in the drift directions of the tectonic plates. On a contextual screen, the user can see additional information, such as the increasing stress beneath the surface. Eventually, as the force reaches a threshold, the fault ruptures, thus deforming the previously created structure along the fault line. With the integration of a physics engine, the user could get an even more compelling look at the devastating forces.

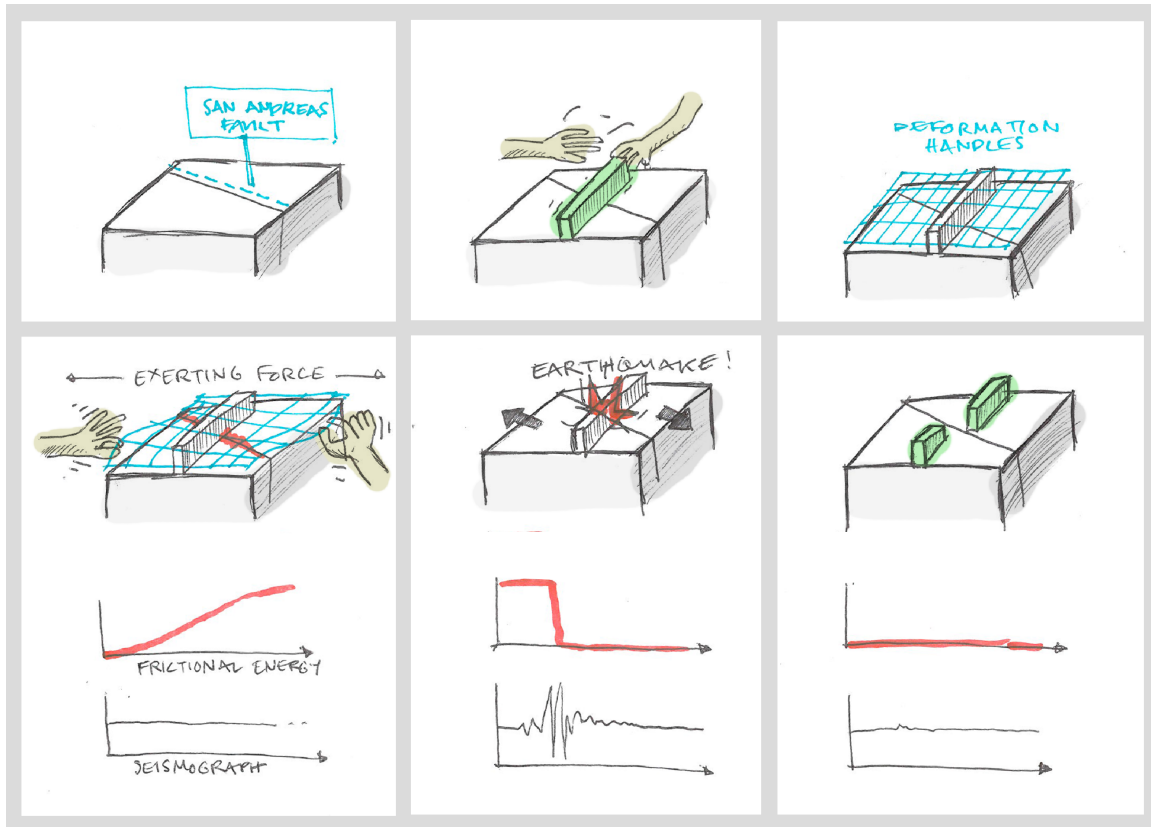


Figure 30: Storyboard for Tangible Earth Science Lab B – Earthquake along a fault

However, as has been pointed out by individuals who have a personal account of the traumatic events people endure during and after natural disasters, there are reservations in regards to a “gamified” experience in which an omnipotent user can unleash a disaster upon a model world. This is obviously a valid concern that needs to be addressed carefully when designing further such scenarios. Accordingly, in many situations it seems better to just imply catastrophic events and allow users to come to their own conclusions, rather than aiming for special effects and turning traumatic experiences into a spectacle.

4.5.2. Further exploration of interaction techniques

A fully implemented system that is able to track and augment physical terrain representations on a surface, as well as in mid-air, would enable interaction at various spatial levels.

- **On and directly above the surface** of the workspace surface: Users will typically stand in front of the workspace surface, and engage with a stack of physical terrain representations through their hands. The physical renderings can be **rear-ranged**, thus re-orienting the projected image, and they can be **taken apart**, thus revealing underlying layers that form secondary displays for simultaneous viewing, but spatially separated views onto the current state of the application.

On this level, users can also interact with the vertical screen that is situated in the back of the workspace surface, through gestures or potentially also a touch surface. The vertical screen serves as a perpendicular view onto the horizontally arranged physical layers. It can also display vertical section cuts that slice through the horizontal plane.

- **In mid-air above** the workspace area: since the physical terrain representations can be lifted up by the user, we can differentiate between interaction with a physical object that is lying on or being moved around on the workspace surface, or an object that is being held up in the air.

An object that is lifted up becomes the **focus layer**: assuming that the user is specifically interested in a specific feature, we can detect which layer she is holding in her hands, and display contextual information or a more detailed view on the vertical screen. We can also implement different interactions depending on where in physical space the user is holding the object. For instance, the edge of the workspace could serve as a virtual **cutting plane**, and moving the physical layer through this plane could display the section slice on the vertical screen.

Similarly, we could present a more **zoomed-in view** on the vertical screen if the user is holding the object closer to her face, or a broad overview if the user is holding the object further apart.

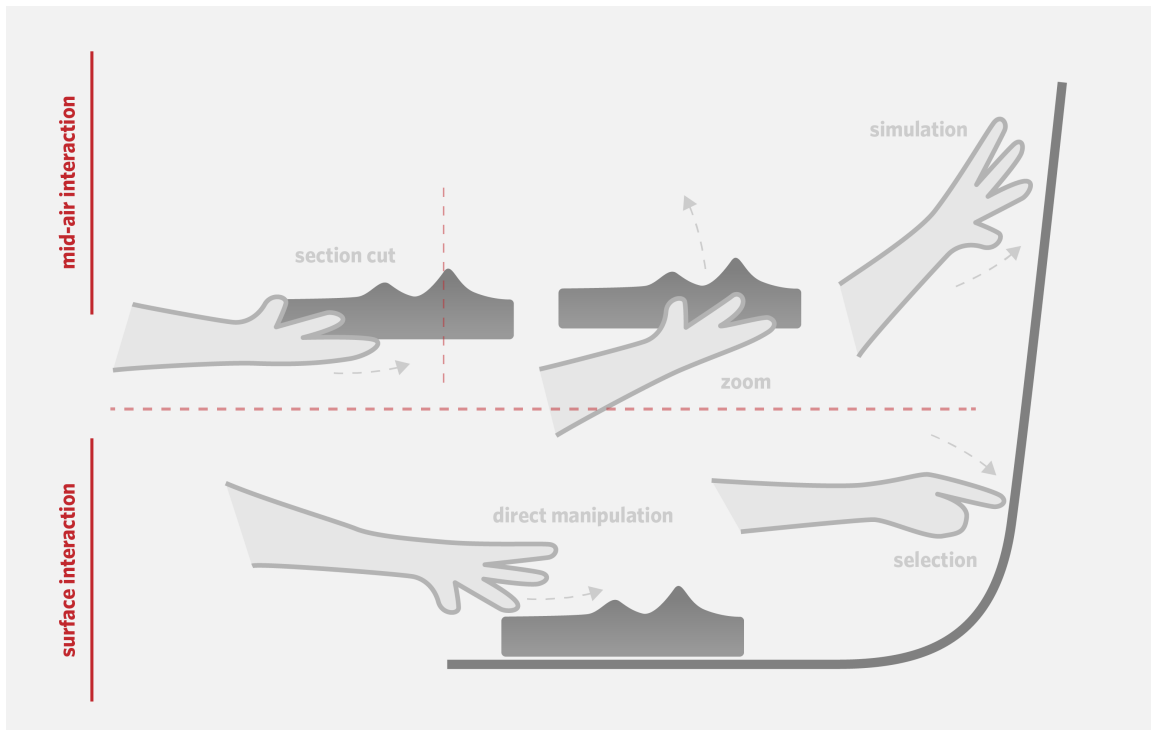


Figure 31: Interaction techniques enabled by the complete system

5. Conclusion

Through the work on the projects described in this thesis, from *GeoSense* to *Stratarium*, we have expanded the tools to aggregate and render environmental data such as digital elevation maps and earthquake alerts in the context of educational tangible interfaces. We have described the design and implementation of a series of interactive systems that integrate geospatial sensor data visualization and terrain models with various user interface modalities to support data analysis and knowledge building using part-digital, part-physical rendering.

Adding to prior work of the Tangible Media Group, we have contributed a concrete application scenario that combines part-digital, part-physical rendering of terrain and related data layers in an environment that “*allowed us to explore a new form of interaction with 3-D tangible information using our bodies*” (Ishii et al. 2012).

Furthermore, we have outlined a “*Designed Environment*” that effectively allows us to construct knowledge by deconstructing objects, and enriching them with data. We have implemented a first interactive prototype of this system, which includes a tool stack that connects the application to the “resource supermarkets” of the World Wide Web, enabling it to load and provide interaction with arbitrary layers of geospatial data. We believe that such interfaces can foster engagement, help us to gain a deeper understanding of our world, inform communities, and render actionable the ever-growing collections of data that we are generating.

We assume that in the future we are going to be able to drastically increase the resolution of shape displays, and potentially also arrange them freely in space or carry with us miniaturized versions. The ultimate form of such displays would be “*future*”

dynamic materials that are computationally reconfigurable” (Ishii et al. 2012). Besides the technical challenges, there are conceptual limitations to our approach, as physical representations of digital data are harder to transport than bits and require that the user possess a “viewer device” or other hardware concoction to access the interface. However, the ideal version of our application scenario based on such materials would enable gestural mid-air control as well as full direct manipulation of the programmable surface, thus enabling a whole new class of compelling interactions enriched with computation. Current technology obviously does not yet provide these possibilities, relegating to the realm of speculation experiments with part-digital, part-physical interactions that would be as compelling as, for instance, simulating in the analog how mountains fold up using nothing more than a dish towel.



Figure 32: “Tangible Geology” – mountain folding as explained to the young author by his mother

In summary, the goal of this thesis work was to combine the richness of interactive geospatial data visualization with the immediacy and educational quality of tangible models, in order to contextualize the visualization and make it more impactful and understandable. We are hoping that this can contribute to the higher-level goal of creating tools for policy-

makers and educators alike that allow us to raise awareness of our planet's fragility, enable discourse and preparedness, and make informed decisions for the future—towards a more resilient global community.

6. Indices

6.1. References

- Ball, Philip. 2002. "Picture This." *Nature* 418 (6893) (July 4): 11-3.
doi:10.1038/418011a. <http://dx.doi.org/10.1038/418011a>.
- Bell, Philip, Bruce Lewenstein, Andrew W. Shouse, and Michael A. Feder. 2009. *Learning Science in Informal Environments: People, Places, and Pursuits*.
http://www.nap.edu/catalog.php?record_id=12190.
- Benko, Hrvoje. 2009. "Beyond Flat Surface Computing." In *Proceedings of the Seventeen ACM International Conference on Multimedia - MM '09*, 935. New York, New York, USA: ACM Press.
doi:10.1145/1631272.1631462.
<http://dl.acm.org/citation.cfm?id=1631272.1631462>.
- Brumfiel, Geoffrey. 2011. "High Radiation Levels Outside Fukushima Evacuation Zone: Nature News Blog."
http://blogs.nature.com/news/2011/03/high_radiation_levels_seen_far.html.
- Butler, Howard, Martin Daly, Allan Doyle, Sean Gillies, Tim Schaub, and Christopher Schmidh. 2008. "The GeoJSON Format Specification." <http://geojson.org/geojson-spec.html>.
- Chen, Jim X. 2005. "Data Visualization and Virtual Reality." In *Handbook of Statistics: Data Mining and Data Visualization*, 800. Elsevier.
<http://books.google.com/books?id=fEgUjUPCtsEC&pgis=1>.
- Cowgill, Eric, Tony S. Bernardin, Michael E. Oskin, Christopher Bowles, M. Burak Yikilmaz, Oliver Kreylos, Austin J. Elliott, et al. 2012. "Interactive Terrain Visualization Enables Virtual Field Work During Rapid Scientific Response to the 2010 Haiti Earthquake." *Geosphere* 8 (4) (August 1): 787-804. doi:10.1130/GES00687.1.
<http://geosphere.gsapubs.org/content/8/4/787.full>.
- CSSSES. 2011. *Ex-post Evaluation of PASR Activities in the Field of Security. Interim Evaluation of FP7 Research Activities in the Field of Space and Security: Crisis Management - Case Study*. Kent, UK.

- http://ec.europa.eu/enterprise/policies/security/files/doc/crisis_management_case_study_cses_en.pdf.
- DeVincenzi, Anthony (Anthony Lawrence). 2012. "GeoSense: An Open Publishing Platform for Visualization, Social Sharing, and Analysis of Geospatial Data". Massachusetts Institute of Technology. <http://dspace.mit.edu/handle/1721.1/76516>.
- Dosenmagen, Shannon, and Anne Rolfes. 2010. "Oil Spill Crisis Map - Initial Analysis and Review." https://mail-attachment.googleusercontent.com/attachment/u/0/?ui=2&ik=4cf9d84733&view=att&th=13e8ee25328231f3&attid=0.1&disp=inline&safe=1&zw&saduie=AG9B_P9AFoyhz0FKH1Yc3WRMO_2g&sadet=1368208756529&sads=0TkhMMoFJr0AlQYzib7MK4e8hHw.
- Dunne, Cody, and Ben Shneiderman. 2012. "Motif Simplification: Improving Network Visualization Readability with Fan and Parallel Glyphs." HCIL Tech Report. <http://hcil.cs.umd.edu/trs/2012-11/2012-11.pdf>.
- Erickson, T. 1993. "Artificial Realities as Data Visualization Environments: Problems and Prospects." In *Virtual Reality - Applications and Explorations*, ed. Alan Wexelblat, 3-22. Academic Press, London. <http://130.203.133.150/showciting.jsessionid=08D19357AF07290B8DA63567D34CADA?cid=1115912>.
- ESRI, National Geophysical Data Center (NGDC). 2004. "Global Digital Elevation Model (ETOPO2)". ESRI. <http://www.lib.ncsu.edu/gis/esridm/2004/help/images/world/etopo2.htm>.
- Fanelli, Gabriele, Thibaut Weise, Juergen Gall, and Luc Van Gool. 2011. "Real Time Head Pose Estimation from Consumer Depth Cameras" (August 31): 101-110. <http://dl.acm.org/citation.cfm?id=2039976.2039988>.
- Grossman, Tovi, and Ravin Balakrishnan. 2008. "Collaborative Interaction with Volumetric Displays." In *Proceeding of the Twenty-sixth Annual CHI Conference on Human Factors in Computing Systems - CHI '08*, 383. New York, New York, USA: ACM Press. doi:10.1145/1357054.1357118. <http://dl.acm.org/citation.cfm?id=1357054.1357118>.

- Haklay, Mordechai. 2013. "Environment and Planning A Abstract." <http://www.envplan.com/abstract.cgi?id=a45184>.
- Indreboe, Alshaikh M., and Larrauri H. Puig. 2012. "Crisis and Recovery Mapping and Analysis (CRMA) and Conflict Reduction Programme (CRP)." In Proceedings of the 9th International ISCRAM Conference. Vancouver, CA.
- Irani, P., and B. Li. 2005. "An Evaluation of Content Browsing Techniques for Hierarchical Spacefilling Visualizations." In IEEE Symposium on Information Visualization, 2005. INFOVIS 2005., 81-88. IEEE. doi:10.1109/INFVIS.2005.1532132. [http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1532132'](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1532132'escapeXml='false'>)
- Ishii, Hiroshi, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. "Radical Atoms." Interactions 19 (1) (January 1): 38. doi:10.1145/2065327.2065337. http://dl.acm.org/ft_gateway.cfm?id=2065337&type=html.
- Ishii, Hiroshi, and Brygg Ullmer. 1997. "Tangible Bits." In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '97, 234-241. New York, New York, USA: ACM Press. doi:10.1145/258549.258715. <http://dl.acm.org/citation.cfm?id=258549.258715>.
- Jansen, Yvonne, Pierre Dragicevic, and Jean-Daniel Fekete. 2013. "Evaluating the Efficiency of Physical Visualizations." In CHI 2013: Changing Perspectives, Paris, France.
- Leithinger, Daniel, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. "Sublimate: State-Changing Virtual and Physical Rendering to Augment Interaction with Shape Displays." <http://tmg-trackr.media.mit.edu:8020/SuperContainer/RawData/Papers/513-SublimateStateChangingVirtual/Published/PDF>.
- Leithinger, Daniel, and Hiroshi Ishii. 2010. "Relief." In Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '10, 221. New York, New York, USA: ACM Press. doi:10.1145/1709886.1709928. <http://dl.acm.org/citation.cfm?id=1709886.1709928>.

- Meng, Liqiu. 2010. "Cartography." In *Handbook of Geomathematics*, ed. Willi Freeden, M. Zuhair Nashed, and Thomas Sonar. Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-01546-5. <http://www.springerlink.com/index/10.1007/978-3-642-01546-5>.
- Mitasova, H., L. Mitas, C. Ratti, H. Ishii, J. Alonso, and R.S. Harmon. 2006. "Real-time Landscape Model Interaction Using a Tangible Geospatial Modeling Environment." *IEEE Computer Graphics and Applications* 26 (4) (July 1): 55–63. doi:10.1109/MCG.2006.87. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1652927&escapeXml=false.
- NASA. 2011. "ASTER Global Digital Elevation Map." <http://asterweb.jpl.nasa.gov/gdem.asp>.
- NSF. 2010. *Earth Science Literacy Principles*.
- OGC. "FAQs - OGC and 'Openness' | OGC(R)." <http://www.opengeospatial.org/ogc/faq/openness/#1>.
- Petsko, Gregory A. 2011. "The Blue Marble." *Genome Biology* 12 (4) (January): 112. doi:10.1186/gb-2011-12-4-112. <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3218853&tool=pmcentrez&rendertype=abstract>.
- Piper, Ben, Carlo Ratti, and Hiroshi Ishii. 2002. "Illuminating Clay." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems Changing Our World, Changing Ourselves - CHI '02*, 355. New York, New York, USA: ACM Press. doi:10.1145/503376.503439. <http://dl.acm.org/citation.cfm?id=503376.503439>.
- Safecast. 2013. "GeoSense Safecast Web Map." <http://map.safecast.org/>.
- Sutherland, Ivan. 1965. "The Ultimate Display." *International Federation of Information Processing* 2: 506–508.
- Tidmarsh. "Tidmarsh Farms, Inc." <http://tidmarshfarms.com/>.
- USGS. "Earthquake Feeds & Data." <http://earthquake.usgs.gov/earthquakes/feed/>.

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