CHIKAKU DB/CAD: A System for Modeling 3D Tectonic Structure

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ABSTRACT

We have developed the systems of reconstructing the 3D computational models of tectonic structure called CHIKAKU DB/CAD as a part of projects for developing simulation software, for the purpose of the clarification of the mechanism of earthquakes, and the prediction of the earthquake wave propagation. The main purpose of the development of CHIKAKU DB/CAD is to manage measured data such as earthquake center points, to edit the upper plate surface from such data, and to offer the data for the numerical simulations of tectonic activity. Today, it is quite difficult to measure the tectonic structure directly. Here we also discuss the method for creating 3D tectonic models of in and around Japanese Islands from given measurement data.

Keywords: Seismographic applications, CAD, Curve/Surface interpolation, B-spline surface.

1. INTRODUCTION

Attempts to clarify global-scale phenomena such as warming of the earth or El Nino effects by using computational simulations are much meaningful and ambitious. The Earth Simulator project [1], a large national project hosted by the Ministry of Education, Culture, Sports, Science and Technology for the purpose of clarification and prediction of such phenomena, was started from 1997 in Japan. The project has already been finished in 2002 whereas the parallel supercomputer named Earth Simulator unfolded the most powerful processor in the world for recent two years.

Our research unit in the Institute of Physical and Chemical Research (RIKEN) independently launched the CHIKAKU project [2] ("CHIKAKU" in Japanese means "tectonic structure") on the solid earth science department of the Earth Simulator project from the very beginning. In CHIKAKU project, we developed a unified software system for the computational simulation of tectonic activity in the area of solid earth science especially in and around the Japanese Islands. CHIKAKU DB/CAD, two of software systems developed in CHIKAKU project, have been released in 2002. These are special modeling systems for constructing solid models of 3D tectonic structure from various types of measured data concerning about the crust activity. We introduce the functionalities of these modeling systems and discuss how to construct solid models from uncertain measured data.

In this paper, we mainly discuss the seismographic applications instead of technical aspects for geometric modeling or CAD. The rest of the paper is organized as follows. In Section 2 we explain the overview of CHIKAKU system. In Section 3 we present CHIKAKU DB and the construction process of grid polygons for a plate surface. We also present CHIKAKU CAD with its functionalities and show results in Section 4, and conclude with describing several future remarks in Section 5.

2. OVERVIEW OF CHIKAKU SYSTEM

In CHIKAKU project, we developed a unified software system based on a non-linear finite element method (FEM) for ascertaining the mechanism of earthquake occurrence and for the prediction of the propagation of seismic waves. To perform such simulations, unstructured finite-element meshes have to be prepared from uncertain measured data. After the simulations, final simulation results accompanied with quite large data sets

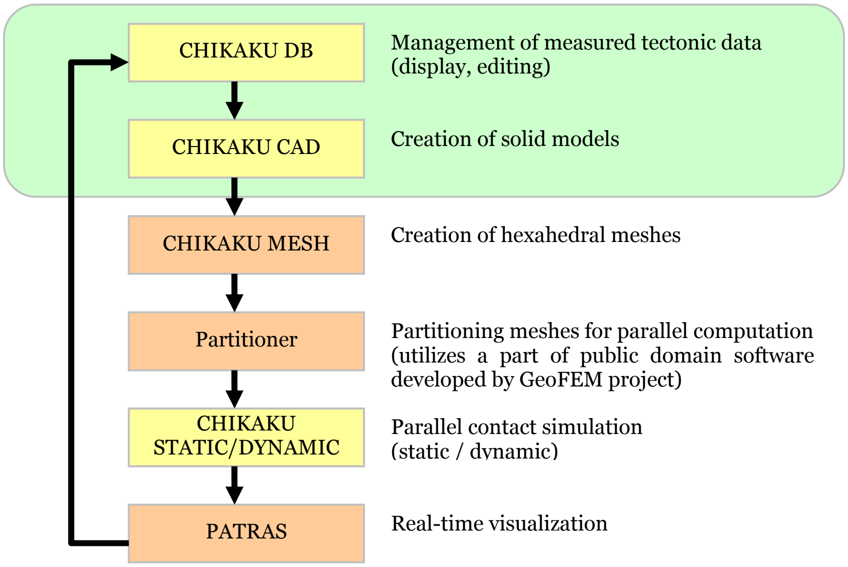


Fig. 1. A framework of CHIKAKU System.

are visualized. Our aim here is to construct a system which brings out a sequence of such procedures seamlessly and efficiently.

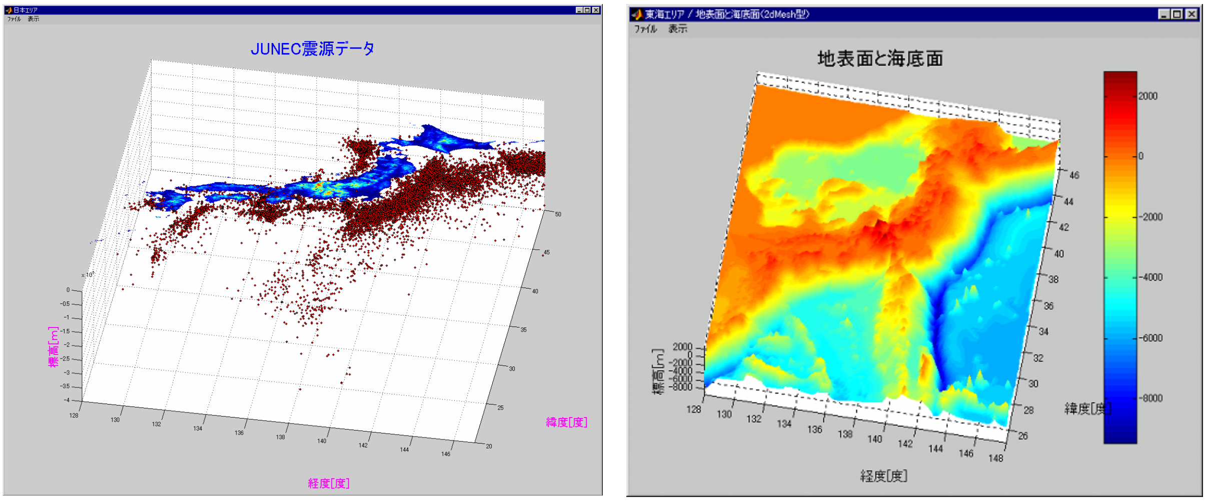
Figure 1 shows a framework of CHIKAKU system. A system is composed of the following six sub-systems: (1) *CHIKAKU DB*. It manages various types of measured data such as earthquake sources, elevation data, GIS outputs, etc. (2) *CHIKAKU CAD*. It constructs solid models of 3D tectonic structure from outputs generated by CHIKAKU DB. (3) *CHIKAKU MESH*. It constructs finite-element hexahedral meshes from solid models. (4) *Partitioner*. It partitions finite-element meshes into a piece of elements for parallel simulations. (5) *CHIKAKU STATIC and DYNAMIC*. These software perform computational simulations based on FEM (using explicit/implicit integration based iterative solver). (6) *PATRAS*. It visualizes simulation results in real-time.

In the above system, we mainly developed (1), (2) and (5). (3) and (6) were developed by Japan Atomic Energy Research Institute, and (4) is a part of public domain software developed by GeoFEM project [3] on the Research Organization for Information Science & Technology (RIST), Japan. Such several research units including ours have closely cooperated with each other to construct a unified framework of a whole software system. A CHIKAKU system was released in 2002 as free software.

CHIKAKU DB and CHIKAKU CAD described later in this paper are first two parts of CHIKAKU system. The development was started on 1998. The current version is 2.0 released on August, 2002. Both of these software run on Windows PC and are freely published for a number of research institutes and universities in Japan related to the research on earthquakes.

Type	**Name of the data**	**Provided by**
Earthquake center	Japan University Network Earthquake Catalog File (JUNEC)	Earthquake Prediction Data Center, Earthquake Research Institute, University of Tokyo
Earthquake center	Japan Meteorological Agency Earthquake Catalog	Japan Meteorological Agency
DEMs on the ground	Numerical Map (50, 250, 10,000) (DEMs)	Geographical Survey Institute
Vectors for GIS	Numerical Map (2500, 25,000) (Spatial Data Infrastructure)	Geographical Survey Institute
Vectors on the ground	Numerical Map (25,000, 200,000) (Coastline)	Geographical Survey Institute
DEMs on the bottom of the sea	3D water depth meshes	Hydrographic and Oceanographic Department, Japan Coast Guard
DEMs on the bottom of the sea	SEAMAP	Geo-data Supply Ltd.
Faults	FAULTL, FAULTG	Hydrographic and Oceanographic Department, Japan Coast Guard

Tab. 1. A part of lists of measured data about tectonic structure in Japanese Islands.



(a) (b)

Fig. 2. Display results of measured data. (a) Earthquake center points of JUNEC. (b) DEMs on the bottom of the sea of SEAMAP combined with DEMs on the ground of numerical map 250.

3. CREATION OF PLATE SURFACES USING CHIKAKU DB

3.1 CHIKAKU DB and Measurement Data

CHIKAKU DB mainly has three components: database functions, display functions and edit functions for measured data. Data needed for the construction of tectonic structure are provided by several institutes. Table 1 shows the list of publicly available measured data concerned about tectonic structure in and around the Japanese islands. Among these data, the current version of CHIKAKU DB can only manage the following four data:

- **Earthquake center** (JUNEC): The data represented with the position of earthquake center and its magnitude for past ten years.
- **DEMs on the ground** (Numerical Map 50, 10,000): DEM (Digital Elevation Model) data computed by using vector data sampled from 1/ 10,000 scale contours map.
- **DEMs on the bottom of the sea** (SEAMAP): The uniform grid data statistically processed from hydrographic samples.
- **Coastline** (Numerical Map 200,000): The data digitalized as the form of vectors from coastlines of 1 / 200,000 scale contours map.

Figure 2 demonstrates two display results of such measured data. Figure 2(a) shows earthquake center points of JUNEC for a year of 1994. Figure 2(b) shows digital elevation models (DEMs) on the bottom of the sea of SEAMAP combined with DEMs on the ground of numerical map 10,000. Although these commercial or non-commercial data are publicly available, a unified data format for these data does not exist. Each data has its own format including, for example, data type (points, arranged grid polygons), and scale of the data (meters, millimeters, and inches) and so on.

For this reason CHIKAKU DB is designed and developed so that different types of external formats can be treated as a uniform internal format. CHIKAKU DB internally manages four types of geometric primitives: points, lines, grid polygons, unstructured polygons. For example, various DEMs such as SEAMAP, numerical map are stored internally by grid polygons data type. Attributes such as magnitudes of earthquake centers can be independently assigned in the above data structure. Other data not described in Table 1 can be converted into one of primitives and are stored if the type of such data can be matched into one of geometric primitives which the software is prepared.

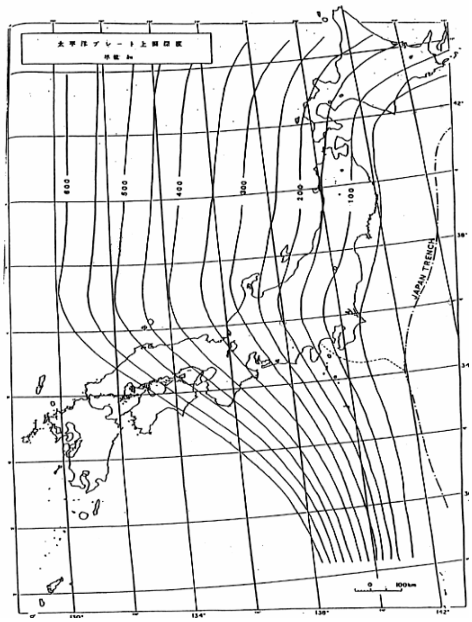


Fig. 3. A contour map of Pacific plate provided by Prof. Mizuho Ishida, NIED, Japan [4].

3.2 Creation of Plate Surfaces

In addition to the functions of managing and displaying measured data, the functions for editing surfaces of tectonic structure are also prepared in CHIKAKU DB. This is for the reason that measured data described in Table 1 only are not enough to represent tectonic structure.

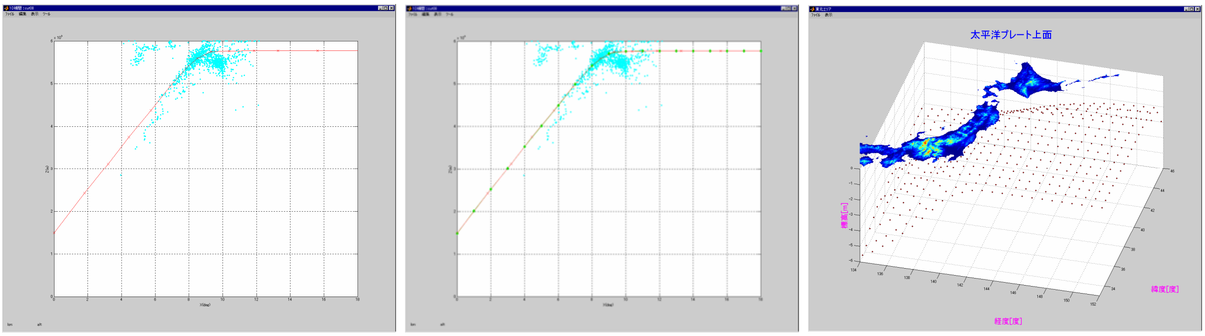
In general, tectonic structure (here we take into account the structure of approximately 100 km underground depth or shallower) is mainly shaped as the subduction of several plates. If we model more detailed structure, the discontinuity of geological layer called faults should be considered in the 5km underground depth or shallower, although the function to model faults is not implemented in the current version of CHIKAKU DB. Earthquake is thought to be arisen by “slipping” the boundary of plates with each other. Consequently, to construct the tectonic structure especially for the numerical simulation of the development process of earthquakes, creating the boundary surface of plate is indispensable.

Figure 3 denotes a contour map of an upper surface of Pacific plate. In addition, other plate surfaces which should be constructed in and around the Japanese islands are: Philippine Sea plate, Mohorovicic discontinuity and Conrad discontinuity. In most cases, these data are provided by physical papers or books, no in electronic form [4].

As is known, it is impossible to construct an exact plate surface even with the current measurement technology because there is no approach to directly measure its shape. Hence, the construction of these data is based on the *estimation* of the surface by seismologists with referring to indirect measured data. This “estimation” is often a main research part of seismologists. Furthermore, there are a lot of different theories for a shape of plate, and then it can not be uniquely determined. For example, a contour map described in Figure 3 is so called “Ishida model” by Prof. Mizuho Ishida, a well-known seismologist at National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. There also exist other models which other seismologists are defined.

Earthquake center points are usually used to help to construct a plate surface. This is because it can be thought of that an earthquake center is regarded as the position which two plate boundary surfaces are slipped, and a plate surface must be laid around these points.

We developed the functions and their associated GUI for editing such plate surfaces instead of digitalizing them recorded by physical papers. To implement the editing functions in CHIKAKU DB, we refer the work model of seismologists [5] which constructed a plate surface in past years. Figure 4 demonstrates a part of results in editing a grid polygon of Pacific plate. A plate surface is constructed by the following steps:



(a) (b) (c)

Fig. 4. The process of construction of grid polygons for a plate surface from earthquake center points.

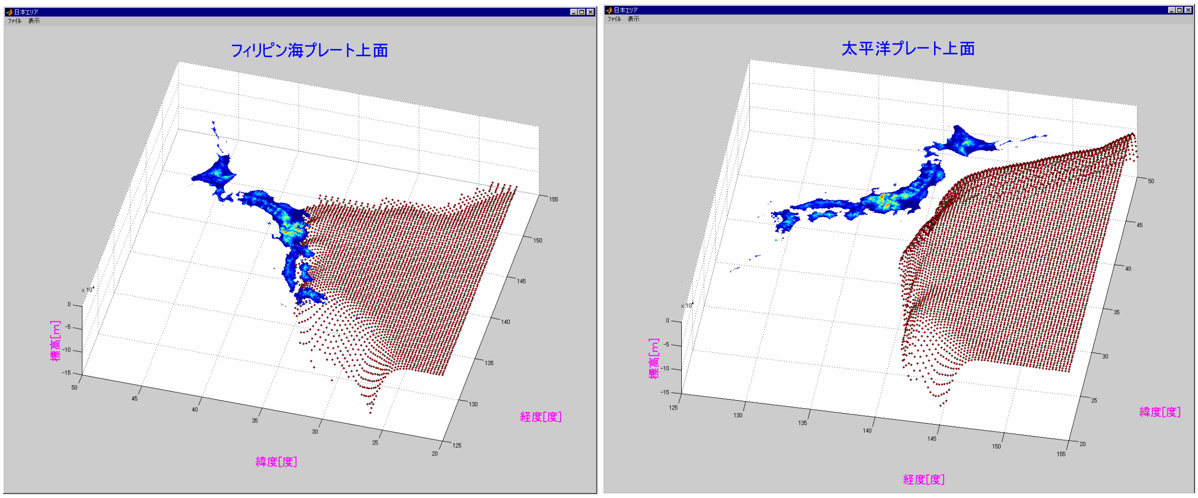
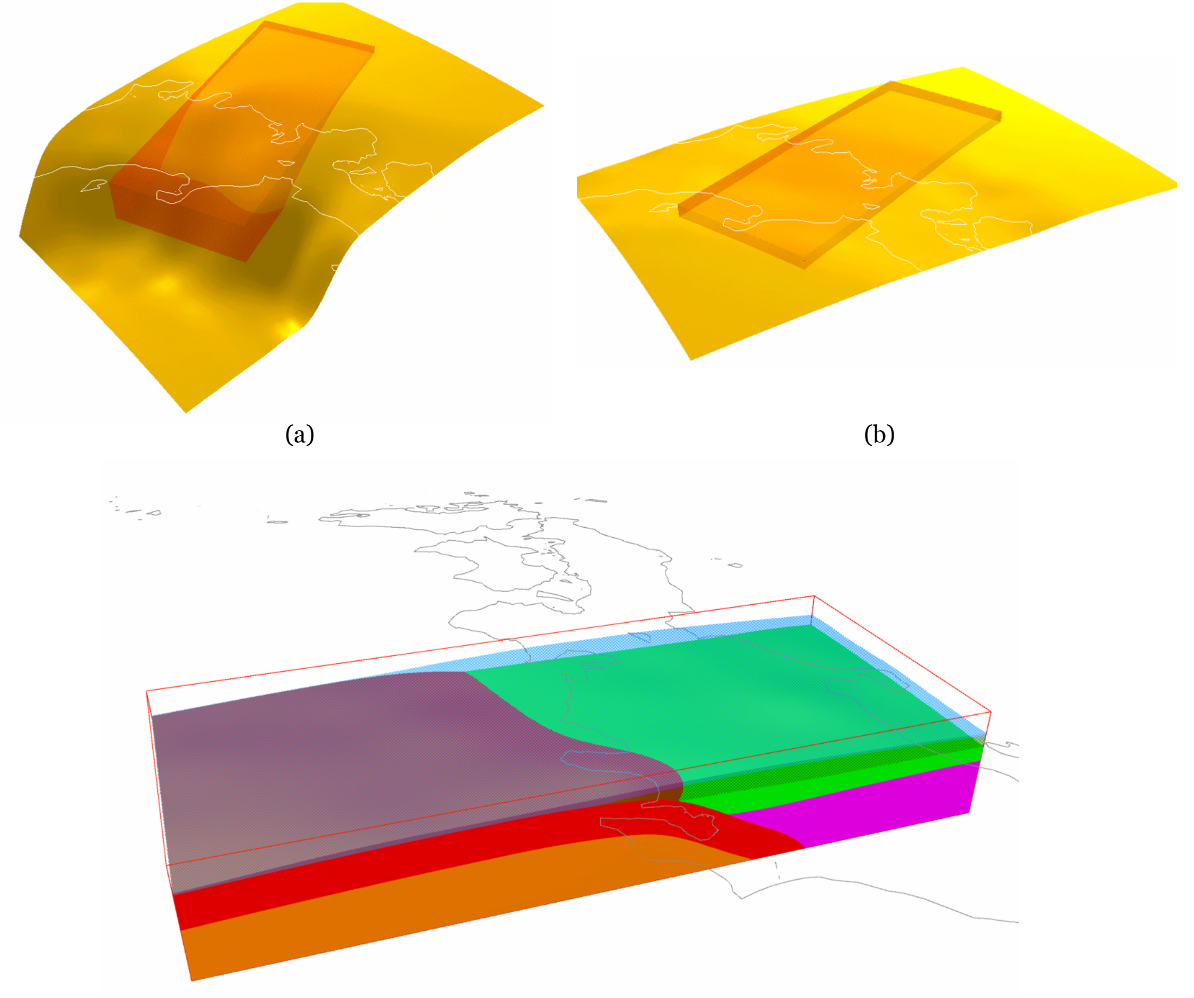


Fig. 5. Display results of grid polygons for plate surfaces. Left: Philippine Sea plate. Right: Pacific plate.

1. Several cut planes are defined in the region where a plane surface is assumed to be included. They are perpendicular to the ground and are equally aligned.
2. Each earthquake center point is projected onto the nearest cut plane.
3. On each 2D cut plane, several points which are assumed to be points on a plate surface are manually defined (Figure 4(a)) referring to the distribution of projected earthquake center points. It is also possible to move or delete these points.
4. An interpolation curve is generated by using input points (Figure 4(b)). From this curve, the equal numbers of points are sampled.
5. After the above 1.- 4. steps are repeated for all of cut planes, a set of sampled points of the same number are aligned on the parallel cut planes.
6. Grid polygons of a plate surface are generated by using all of these sampled points (Figure 4(c)).

Three types of methods for curve interpolation and surface interpolation, linear interpolation, cubic interpolation and piecewise cubic Hermite interpolation, are provided in CHIKAKU DB. Figure 5 shows grid polygons of Philippine Sea plate and Pacific plate created by the above functions.



(a) (b)

(c)

Fig. 6. Construction of a solid model for tectonic structure of Tokai region.

4. CONSTRUCTION OF SOLID MODELS USING CHIKAKU CAD

The purpose of the development of CHIKAKU CAD is to offer solid models needed for computational simulations of tectonic activity by using outputs from CHIKAKU DB. Unstructured hexahedral or tetrahedral meshes are required for such simulations. To construct unstructured meshes by mesh generator software (CHIKAKU MESH in our system), solid models are also needed. Prior to the development of CHIKAKU CAD, we first developed and evaluated a prototype CAD system based on a commercial mechanical CAD [6]. Although commercial CAD systems tend to have enough functions to construct tectonic solid models, they are too redundant since a lot of functions which are not needed for constructing are also implemented. A commercial CAD system tends to be designed as the general-purpose software, and then its processing speed is generally slow. Furthermore, a system based on commercial software is too expensive to distribute to research institutes as free software.

Based on feedbacks from the prototype system, CHIKAKU CAD is proprietary designed and developed. The number of functions to be developed to construct tectonic solid models is minimized as much as possible. Note that the usage of CHIKAKU CAD is limited to the construction of solid models for computational simulations of

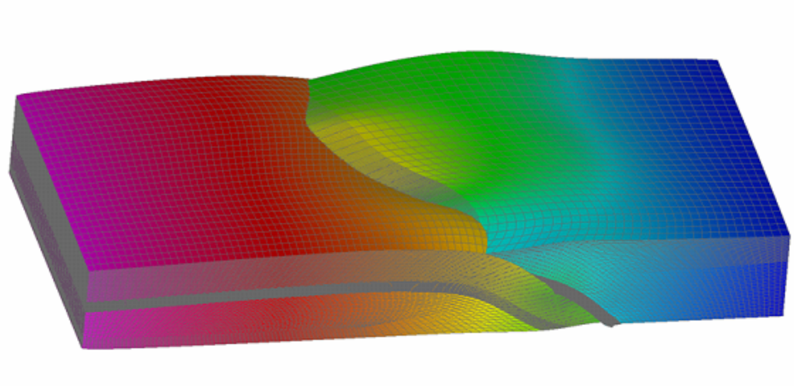


Fig. 7. Computational simulation result of Tokai region in Japan by CHIKAKU STATIC. A hexahedral mesh is generated by CHIKAKU MESH.

tectonic activity, compared to CHIKAKU DB which is expected for wider use. Consequently, CHIKAKU CAD is developed independently as stand-alone software.

The main functionalities of CHIKAKU CAD are listed as follows:

1. **Input grid polygons and generate free-form surfaces**: From grid polygons of CHIKAKU DB for plate surfaces, free-form surfaces are generated by surface interpolation. B-spline surfaces are used in CHIKAKU CAD.
2. **Create a rectangular solid model**: A rectangular solid is defined by user-specified latitude, longitude and underground depth. This is a base solid of tectonic structure (an orange-colored box in Figure 6(a)).
3. **Cut a solid by surfaces**: A solid model is cut by a free-form surface. Plate solids are generated by this function.
4. **Output solid models:** A solid model with IGES format is read out to hand it over to mesh generation software.

Figure 6 demonstrates the results of constructing solid models. Figure 6(a) and 6(b) show free-form surfaces of Philippine Sea plate and Conrad discontinuity respectively. Figure 6(c) shows a solid model of Tokai region in Japan from a rectangular solid and several plate surfaces. A solid modeling kernel as a geometric processing engine to establish these functionalities is developed using GHL (Geometric Handling Library) [7] by PML Inc. Figure 7 shows the computational simulation result of CHIKAKU STATIC using a hexahedral mesh of Tokai region as shown in Figure 6(c) created by CHIKAKU MESH.

5. CONCLUDING REMARKS

In this paper we have described the overview of our developed CHIKAKU DB/CAD and the construction process of 3D solid models of tectonic structure in and around the Japanese islands. These software are developed so that they are really usable for seismologists, and then the limited functionalities for their uses are designed and implemented.

For future development of the software, several additional functionalities should be considered. Firstly, inputs from volume data have to be supported to accommodate feedbacks from the visualization results of FEM computations. Secondly, in our software only solid models for regions composed of several plates can be constructed. Those regions are the range from approximately 5km to 100km underground depth. More shallow and complicated regions including faults are currently out of range in our software. However, modeling such regions is more important to simulate for the prediction of the earthquake wave propagation. Finally, physical attributes used in computational simulations can not be entered in our current software. A unified management of geometrical and physical attributes is also important to be of more general use for seismologists.

We are currently constructing the more detailed version of tectonic structure covered for a whole region of Japanese Islands together with seismologists.

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