Sellafield (Nirex), Wellengerg (Nagra), Äspö HRL (SKB) and Yucca Mountain (USGS, USDOE) [18].

Minimum tension theory based on spline interpolation is one of the functions of EarthVision. It is applied to estimate the ground surface, geological boundaries and fault planes. This method interpolates between adjacent data with the smoothest curved surface by an n-dimensional polynomial formula based on the input data of positions and directions [19].

4.1.2 Geological results – JNC's geoscientific research prior to Phase I-a of the MIU Project

The geology and geological structures in and around the Shobasama Site were investigated prior to the MIU Project in what is termed in this report "other geoscience research". This research includes surveys on the Tsukiyoshi uranium deposits [20,21], the RHS Project [15], the Shaft Excavation Effect Experiment [22], investigations in the Tono Mine and historic geological knowledge available from literature surveys. Following is an overview on the other geoscience research.

4.1.2.1 Lineament definition, analysis and interpretation [15]

It is generally accepted that a lineament refers to a linear topographic feature (sometimes a geophysical linear) possibly related to an underlying structure such as a fault, fracture zone or lithologic contact. Generally, a linear topographic feature is visible on aerial photographs or satellite imagery such as Landsat or SPOT [23]. Structures such as faults and fracture zones often, though not always, have a linear topographic expression. Therefore, lineament analyses may provide a rapid method to develop knowledge of the location of individual structures and also, from a statistical analysis of lengths and trends, can provide a basis for conceptualization of structural patterns and a preliminary indication of regional deformation.

In the RHS Project, TGC used Landsat Thematic Mapper multi-spectral imagery with a ground level resolution of 30 m (1:200,000 scale) covering an area of 50 km square. As shown in Figure 4.1(1), 1,276 lineaments were identified, including ones coincident with known active faults [14] such as the Adera Fault, Ako Fault, Hanadate Fault, Shirakawa Fault, Byobusan Fault, Kasahara Fault, Enasan Fault and Sanageyama-Kita Fault.

These faults form a grid-like pattern and are interpreted to form the boundaries of several large blocks. The trends of lineaments in each fault-bounded block, the intra-block, were compared statistically. It was clear that, as is shown in Figure 4.1(1), there are differences in the distribution patterns of lineament trends among the blocks. This may suggest that, if we assume the lineament is a reflection of discontinuities such as faults, there are regional differences in tectonic patterns related to variations in stress conditions and deformation in the blocks. The reasons for the inter-block variations are not clear: they could be due to stress redistribution during tectonic events resulting in different deformation patterns or due to the underlying geology. Nevertheless, from conceptualization of geological models and a predictive perspective, the lineaments are useful. In addition, whether related to stress redistribution or internal geological fabrics, each block can be assumed to have had a slightly different evolution of the geological structures [24].

In the RHS Project, more detailed lineament interpretations have been carried out in the larger area around Tono Mine and the Shobasama Site; the area bounded by the Ako, Byobusan, Hanadate and Shirakawa Faults (Figure 4.1(1)). Because observations and results might be different if imagery with different scales and availability of stereoscopic views are used, analysis at this scale was done using three kinds of imagery.

(a) Landsat TM imagery (1/200,000)
(b) French SPOT satellite photographs (High Resolution Visible Imaging System) with ground resolution of 20 m (1:100,000 scale)
(c) Stereoscopic aerial photographs (1:40,000 scale)

The results were compiled and analyzed separately. As a result, in this area many large and small lineaments were recognized, including lineaments coincident with the active faults such as the Byobusan, Kasahara and Ako Faults. More than ten lineaments longer than 3 km [23] were recognized in the Tono Mine area. These are considered to correspond to faults or fracture zones because of their length and continuity. In addition, NW-SE, NS and NNE-SSW trending lineaments are prominent. Some correspond to known faults [20] such as the Yamada Fault Zone and the Shizuki Fault.

As a result, ten blocks with unique patterns in lineament orientation distributions were recognized. Structural discontinuities such as faults and joint zones are considered to have formed due to variations in tectonic stress distributions resulting in slightly different deformation patterns. Therefore, each of the ten blocks is regarded as having been subjected to somewhat unique stress conditions and deformation. Those ten blocks are shown in Figure 4.1(2) [25]. The Shobasama Site is located in the 'f' block in this Figure.

4.1.2.2 Ground geological surveys

Ground geological surveying is intended to obtain basic data on geology and geological structures by surface mapping and observation to produce geological maps. The geological map is the fundamental tool for displaying geological knowledge and thus is the keystone to development of the geological model.

The Shobasama Site and the neighboring areas have had a geological map [15, 26] produced in the RHS Project. These maps depict the lithological variety and internal structure (faults and fractures) in the Toki Granite. As well, some excellent geological maps produced for earlier mapping projects are available [12,13, 20, 21].

Geology [13, 15, 20, 21, 26]

The geology, as it is known from the earlier work, is as follows. The basement is composed of Paleozoic and Mesozoic formations intruded by granites. The basement is unconformably overlain by Neogene to Quaternary Mizunami Group sedimentary rocks (Figure 2.3 (a)) in the vicinity of the Shobasama Site. The Mizunami Group is in turn overlain by the Seto Group with a distinct unconformity.

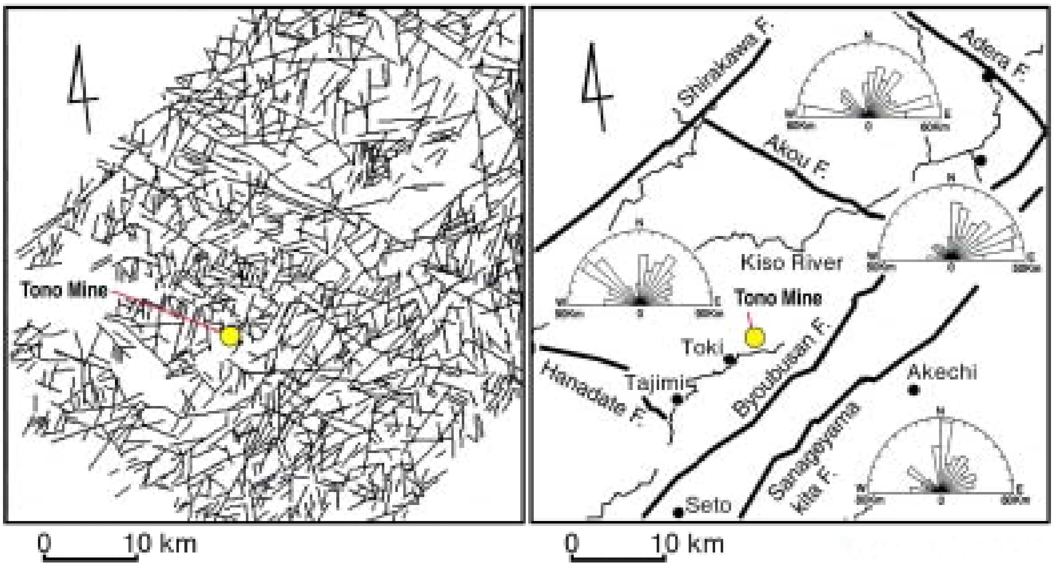

Figure 4.1(1) Lineament interpretation in the Tono district and lineament rose diagram for each fault-bounded block (top)

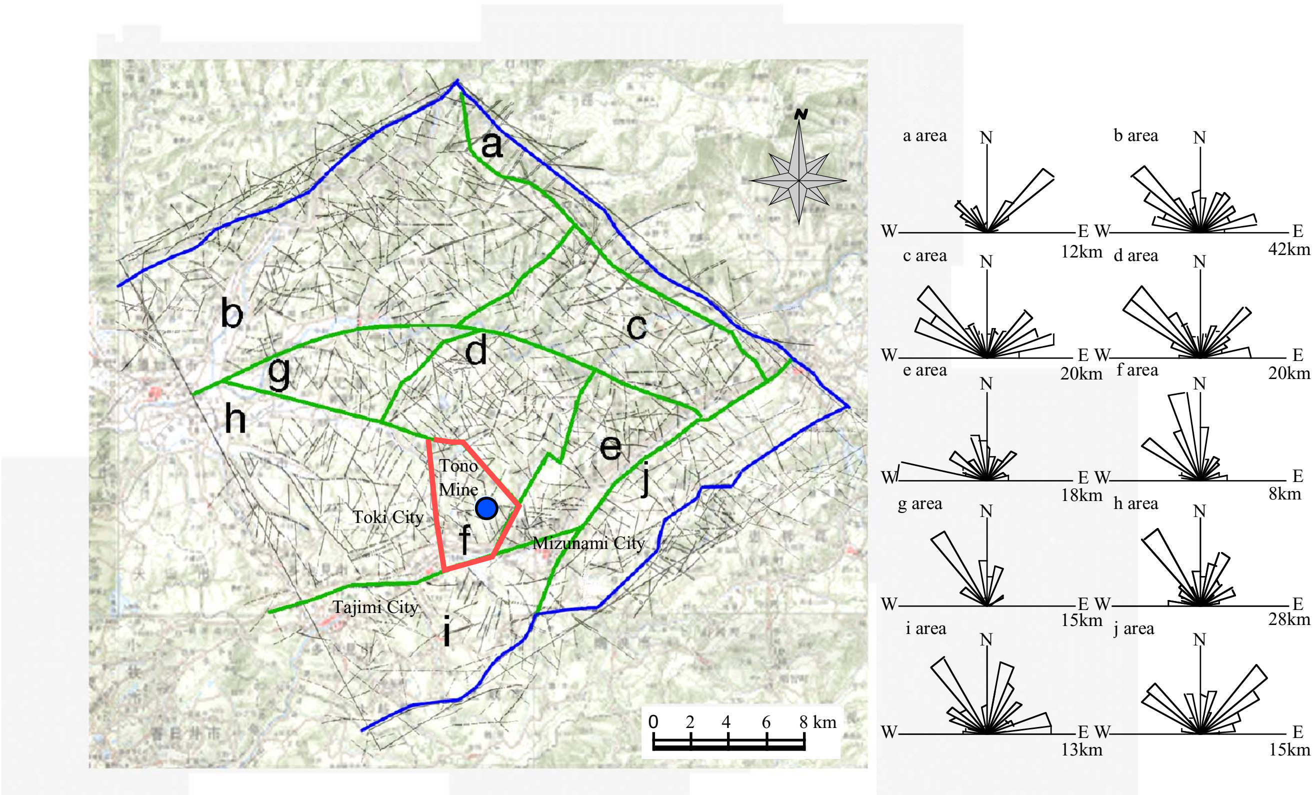

Figure 4.1(2) Division based on the result of the lineament interpretation and rose diagram

Basement rocks

At the Shobasama Site and the surrounding area, the Toki Granite forms the basement rock. The Toki Granite intrudes sedimentary rocks of the Mino Belt on its south, west and north sides. On its northeast and southeast sides, the granite intrudes the Nohi Rhyolite. The Toki Granite adjoins and is probably related to a Ryoke Granite known as the Sumikawa Granite. The intrusive contacts of the Toki Granite with sedimentary rocks of the Mino Belt and the Nohi Rhyolite are clearly defined at surface, and the nature of the contacts is well known. On the other hand, the contact with the Sumikawa Granite cannot be confirmed at surface because both granites are lithologically quite similar.

The Toki Granite is divided into three textural facies based on grain-size;: coarse-grained, medium-grained and fine-grained biotite granite. The center of the granite (Hiyoshi district of Mizunami City to Jorinji district of Toki City) is fine to medium-grained biotite granite. It is surrounded by coarse-grained biotite granite. Near the contact with the sedimentary rocks of the Mino Belt, especially at the contact, the Toki Granite tends to be fine-grained. This is confirmed at Takodo district of Mizunami City where a transition from coarse- to medium- to fine-grained is observed.

Sedimentary rocks

Sedimentary rocks of the Mizunami and the Seto Groups form the cover rocks in the vicinity of the Shobasama Site. The Mizunami Group has been divided into the Toki Lignite-bearing Formation, Akeyo Formation and Oidawara Formation in ascending order.

・Mizunami Group

The group consists mainly of pyroclastic materials and granitic clasts, occasionally yielding silicified wood and organic remains (large fossils of mollusks and plants). It generally decreases in grain-size upward, composed of silty rocks in the uppermost part. While the Toki Lignite-bearing Formation consists of arkosic sandstone and conglomerate containing granite cobbles to boulders unconformably overlying the Toki Granite, the Akeyo Formation is composed mainly of medium-grained tuffaceous sandstone. The Oidawara Formation is composed mainly of fine-grained tuffaceous sandstone and siltstone. Several unconformities occur through the sequence.

・Seto Group

The Seto Group unconformably overlies the Mizunami Group. It is composed mainly of conglomerate containing granules to cobbles, with a few layers (1 to 3 m thick) of clay and sandy clay intercalated in the lower part. Constituent gravels of the conglomerate are composed of granite, chert, rhyolite, mudstone and volcanic rocks, while the matrix is white-colored tuffaceous or arkosic.

Geological structure

The geological structure in the region is complex, as shown by the maps of the known active faults and several detailed studies done near the Shobasama Site to correlate outcrop scale of fracturing with nearby lineaments. The evidence of vertical movements recorded in the sedimentary sequences by the unconformities is indicative of potential reactivation of earlier faults and thus the potential for multiple deformation/reactivation events. The type of faulting is also complex, with evidence of reverse, normal and strike slip faults. Large porphyry dykes also intrude the Toki Granite; in some instances coincident with linear valleys/rivers.

・Faults

There are a number of known faults in the Shobasama Site. The Yamada Fault and the Shizuki Fault are nearby. Others are shown on the regional geological maps. The Tsukiyoshi Fault is known to occur at the Tono Mine and is thought to occur east and west at surface in the vicinity of the Shobasama Site [12, 20, 21]. It is visible in a gallery of the Tono Mine where fault gouge centimeters thick are recognized. The Tsukiyoshi Fault is a reverse fault with a strike of N80°W, a dip of 70° and an estimated throw of about 30 m. In-depth studies of the fault in the mine indicate it to be a barrier to groundwater flow across the fault.

・Fractures in granite

Fracture investigations in the RHS Project include mapping and photographing of fractures in outcrop as well as measurements of various parameters of the fractures as are shown in Table 4.1 [15].

Table 4.1 Observed characteristics of fractures

Shape of fracture	Planar Fracture, Irregular Fracture, Curved Fracture, Stepped Fracture
Shape of fracture (detail)	Flat Plane, Curved, Undulating, Stepped, Braided
Structure of fracture plane	Smooth, Rough, Slickensided
Visibility of fracture ends	Both/One/Neither end is covered
Structure of the end of fracture	Obscure/Clear/Forked/Horsetail/Braided/Stepped
Spatial relation to other fractures	Not intersected/Intersected/Contacted
Direction of movement	
Dip/Strike	
Length	Distance between both ends or visible length (0 or 1 end)
Width	Distribution width of microcrack along fracture/Average of amplitude of crack
Aperture	
Filling minerals	
Width of alteration in wall	
Spring (artesian condition)	The amount and pH
Others	Remarkable characteristics

It was clear that two trends (NNW-SSE and NE-SW) of fractures are dominant in the Toki Granite. These trends are coincident with lineament trends in this area. Small faults are recognized in outcrops, but large-scale faults in outcrop were not found.

Quartz porphyry dikes (steeply dipping, several tens of meters wide) are known to intrude in the central (Kawai district, Toki City) and southern parts (Dachi district, Toki City) of the Toki Granite. The strikes of those dikes are mostly NS to NNW-SSE. Small-scale dikes are observed as quartz veins (less than 10 cm wide) at the periphery of the granite with NNW-SSE strike. The strikes of those dikes tend to be N-S to NNW-SSE. It is assumed that fractures with this orientation were open (i.e. tensional fractures) when the dykes intruded to the granite. However, some dikes with the same strikes have clearly been sheared .

Therefore, the evidence in the fracturing implies a complex deformation history.

To determine any relationship between lineaments and fractures, the strike of fractures at selected outcrops was compared with that of a corresponding lineament, that is, a lineament near or adjacent to the outcrop. The results show that orientation trends of both often match well. Each of the ten blocks referred to in Section 4.1.2, and Figure 4.1(2) appear to have different prevailing fracture trends as is shown in Table 4.2. It shows that the prevailing fracture trend is consistent with lineament trends in each block.

Table 4.2 Prevailing strikes of fractures and lineaments in each block

Block	Fracture strike	Lineament trend
d	**NE-SW**, NNW-SSE, ENE-WSW	**NE-SW**, NW-SE, EW
e	**EW,** NS	**EW**
f	**NS,** NE-SW, WNW-ESE, **NW-SE**	**NS**, NNW-SSE, **NW-SE**
h	EW, NS, NNW-SSE	NW-SE, NNE-SSW
i	**NW-SE**, NS	**NW-SE**, NNE-SSW, EW
j	**NE-SW**, WNW-ESE, NS	**NE-SW**, NW-SE

It implies that it may be possible to estimate or predict dominant fracture trends using the trend of the lineaments in the respective block.

4.1.2.3 Ground geophysical survey

Regarding ground geophysical surveying, the results of a ground electromagnetic survey in the RHS Project are available. It was carried out to estimate the thickness of the sedimentary cover and depth to the conformity between sedimentary rocks and granite and the location of structures in the granite. Furthermore, the results of reflection/refraction seismic survey, carried out to understand the geology and geological structure in the RHS Project and Shaft Excavation Effect Experiment are also available. Details of those surveys are shown in Tables 4.3 and 4.4. Dynamite as well as small-size hydraulic impactors (Table 4.5) was used as seismic sources.

Table 4.3 Details of ground electromagnetic survey

	Data stations	Dipole length	EM source	Distance from EM source	Data acquisition mode	Radio frequency range	Radio frequency for sampling	Data amount*
CSMT	144	30 m	Artificially induced	200-350 m	HF	750Hz-96kHz	192 kHz	3 counts/radio frequency
MT	144	30 m	Natural induced	—	HF	10Hz-1kHz	12 kHz	30 counts per /measurement point

*** 1count＝4,096 points×3 stacks**

Table 4.4 Details of reflection / refraction seismic survey

Reflection seismic survey (See Figure 4.4)	Line-R-1 (1,700 m)	・Seismic source : dynamite ・Seismic source interval : 70 to 160 m ・Receiver interval : 10 m
	Line-R-2 (1,900 m)	・Seismic source : dynamite ・Seismic source interval : ca.100 m ・Receiver interval : 10 m
Refraction seismic survey (See Figure 4.4)	Line-2-1 (500 m) Line-2-2 (500 m) Line-2-3 (500 m)	・Seismic source : dynamite ・Seismic source interval : 5m ・Sampling rate : 1msec ・Data length (Recording time): 1sec
	Line-1 (650 m)	・Seismic source : Impactor ・Seismic source interval : 4 m ・Sampling rate : 1msec ・Data length (Recording time): 1sec

Table 4.5 Details of small oil pressure impactor

Size Length, Width, Height	Weight	Impact energy	Rod weight	Baseplate weight	Impact frequency	Maximum tilt angle
2.5 m, 1.0 m, 2.2 m	1.2 t	2000 J	65 kg	65 kg	10 sec	±30 °

Ground electromagnetic surveys (MT and CSMT methods) (15,27)

MT (Magneto-Telluric) method is a way to estimate subsurface resistivity distribution using natural or artificially induced electromagnetic signals (geomagnetism). In this survey, both natural and artificially induced signals are utilized by the MT and CSMT methods, respectively. Data was collected at 144 stations and two components for both electric and magnetic fields were measured. For each point, one-dimensional analysis, assuming a horizontal multi-layered structure is performed. Two-D analysis was carried out for five survey lines, as is shown in Figure 4.2.

A horizontal resistivity distribution map of the one dimension analysis, at an elevation of 200 masl (Figure 4.3) reveals extensive low resistivity areas around the Mizunami sedimentary basin. These occur towards Tono Mine to the west, and towards Shirakura, Hosokute and Shukubora to the north. Another low resistivity area is found in the NW part of study area, from Misano to Tsubashi. According to the results of resistivity logging, it is estimated that resistivity lower than 80 Ωm corresponds to sedimentary rocks of Seto and Mizunami Groups, while areas with higher than 80 Ωm corresponds to granite and other basement rocks. Therefore, low resistivity areas may correspond to an ancient river channel structure on the surface of the granite.

Figure 4.3 shows that low resistivity areas corresponding to the sedimentary rocks do not extend to deeper than 0 masl. It is estimated that the area deeper than 0 masl elevation is occupied by high resistivity basement rocks. This is consistent with the results obtained by borehole investigations. Also it indicates that the depth distribution of the unconformity between granite and sedimentary rocks can be estimated using this resistivity survey method.

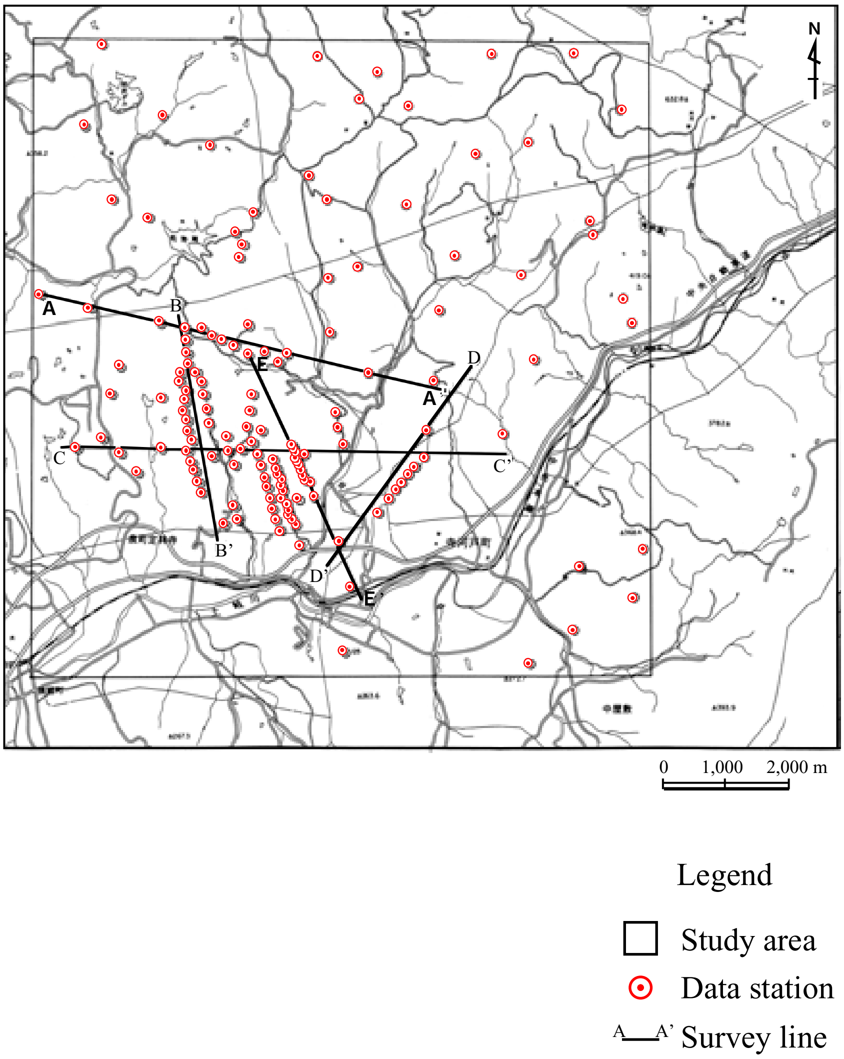

Figure 4.2 Data stations and survey lines of electromagnetic survey

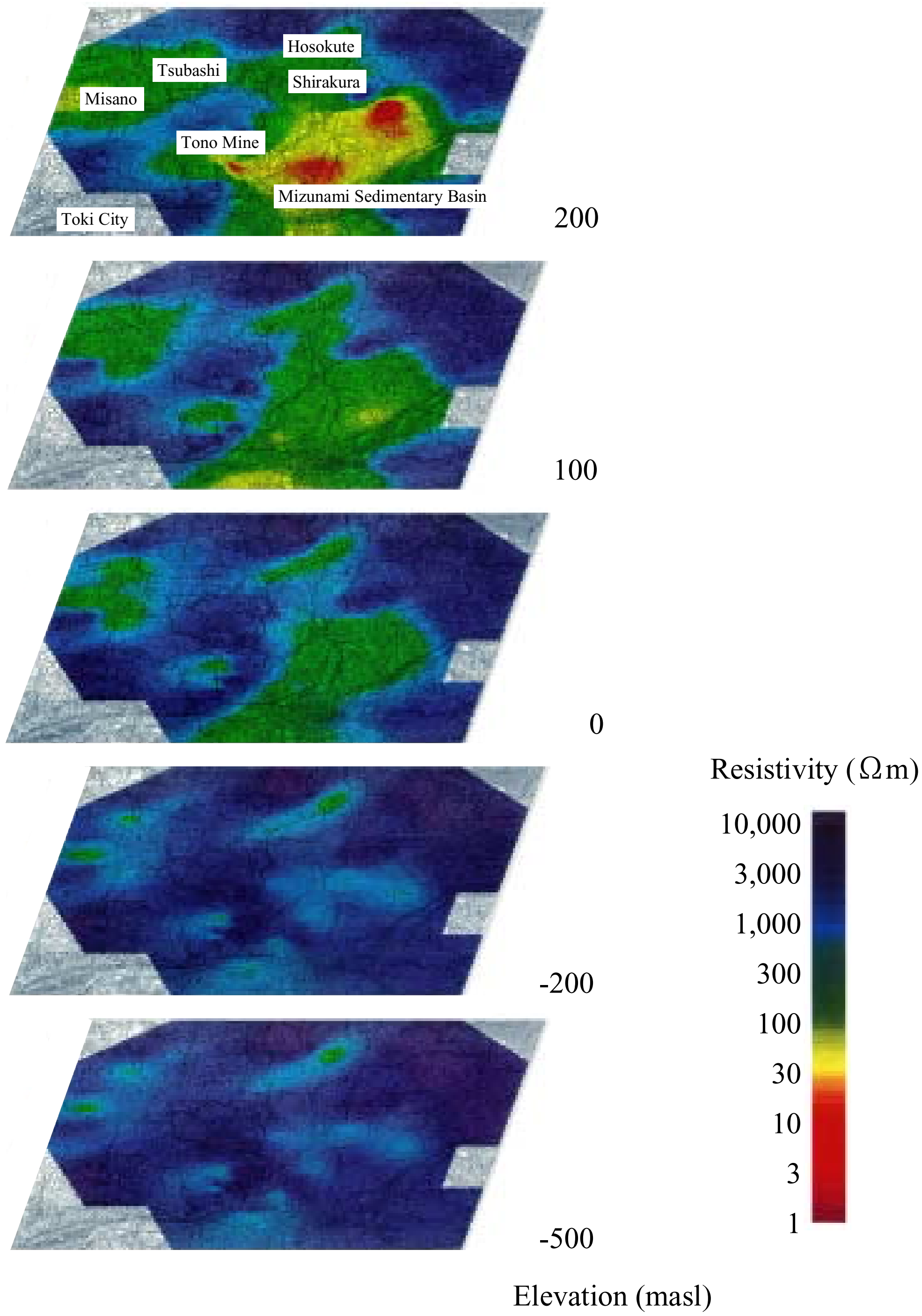

Figure 4.3 Resistivity distribution by elevation based on the result of ground electromagnetic survey

Refraction seismic survey [15,28]

A refraction seismic survey uses seismic waves artificially generated on or under the ground surface. These waves, which refract on bedding planes, are monitored on the ground surface. Using the difference in arrival times of the seismic waves at different measurement points, estimates of seismic wave velocity and the thickness of each layer can be determined. This method has been widely used to determine geological structure and rock condition in the fields of resource exploration and civil engineering.

The length of the survey line was established taking the thickness (up to about 150 m) of Neogene strata into consideration (Table 4.4, Figure 4.4). Receiver interval is 10 m, and source interval is 70 to 160 m.

As is shown in Figure 4.5 (Survey Line-R-1), the Neogene strata are divided into three undulatory but approximately sub-horizontal units based on seismic wave velocity. Also, the depth and shape of the unconformity between Neogene strata and granite are estimated. The results are consistent with the data obtained from the boreholes near the survey line. The seismic wave velocity of the granite is 4 km/s under the valleys, while it is 5 to 6 km/s under the hills on both sides of the valley. It implies that the fractures have developed more under valleys than under hills.

The fracture zone accompanying the Tsukiyoshi Fault may correspond to the low velocity zone (1.2 km/s) at 519 to 568 m on the survey line. The width of the fracture zone is estimated to be about 50 m, much wider than the width of the clay observed along the fault in sedimentary rocks. Also, two other low velocity zones are recognized:

- NE of Tsukiyoshi Fault, 271 to 350 m on the survey line: (velocity: 1.7 km/s) (200 m away from the Tsukiyoshi Fault)
- SW of Tsukiyoshi Fault, 1,333 to 1,362 m on the survey line: (velocity: 0.6 km/s) (800 m away from the Tsukiyoshi Fault)

This implies existence of other faults or possibly secondary faults related to the Tsukiyoshi Fault.

Reflection seismic survey

This survey gives higher resolution than the other geophysical surveys. Also, it can be used to determine geological structures in two dimensions. For these reasons, it is widely used in many kinds of study.

As is shown in Figure 4.6, the geological structures to 200 m depth below surface were estimated [15, 29]. In this cross section, the Tsukiyoshi Fault is represented by discontinuous reflections within the Neogene strata. The result also shows the possibility of previously unknown subordinate faults.

One of the results of the reflection seismic survey carried out in the Shaft Excavation Effect Experiment in Tono Mine is shown in Figure 4.7. Also in Figure 4.7, the cross section of the same kind of survey carried out for Tsukiyoshi Uranium deposit is shown. Nine reflection planes recognized by this survey roughly coincide with the geological strata: the top of the Akeyo Formation, a bedding plane in the Akeyo Formation, the top of the Upper Toki Lignite-bearing Formation, the top of the Lower Toki Lignite-bearing

Formation, two bedding planes in the Lower Toki Lignite-bearing formation and the top of the basement granite.

4.1.2.4 Borehole investigations

Borehole investigations were mainly carried out to study the sedimentary rocks overlying the Toki Granite. For example, surveys were done for the Tsukiyoshi uranium deposit (20,21), the Shaft Excavation Effects Experiment at Tono Mine and other geoscientific research (12 TH-series boreholes (22), 8 AN-series boreholes, 6 SN-series boreholes and 1 HN-series borehole) (30) (Figure 4.8). The borehole investigations confirmed the stratigraphy estimated by the ground geological surveys.

Contour maps (20,21,31) of the basement rock in the Tono area compiled through borehole investigations and surveys on the Tsukiyoshi uranium deposit indicate that there is a paleo-river channel on the erosion surface of the basement granite.

Borehole investigations carried out for the Shaft Excavation Effects Experiment revealed a correlation between the lithofacies (e.g. grain-size) of sedimentary rocks and their apparent resistivity/permeability obtained by electrical logging. These surveys also reveal the high permeability of the conglomerate layers in the Lower Toki Lignite-bearing Formation and that the Oidawara and Upper Toki Lignite-bearing Formations have low permeability (32,33).

Investigations carried out at the Shobasama Site included drilling of the AN-1, 2 and 3 boreholes, core descriptions (34), geophysical logging and BTV surveys to develop methodologies and techniques for rock mass evaluation (Table 4.6). The results of borehole investigations in AN-1 indicate that the granite could be divided into three domains according to shapes of fractures, the varieties/characteristics of fracture fillings and the fracture density (35). These are Domain I: Ground level (GL) to 300 m depth; Domain II: 300 m to 420 m depth; Domain III: 420 m to bottom of borehole). The results of testing of radar instruments carried out in AN-1 and 3 indicate the presence of a zone characterized by high decay rate (attenuation) of electromagnetic wave amplitude between the ground surface and about 150 m depth (36). However, there is no more information on the horizontal continuity of these domains and the high decay rate zone. Thus it is not clear whether or not this observation is applicable to the surrounding rock mass nor that it might be representative of the entire Shobasama Site.

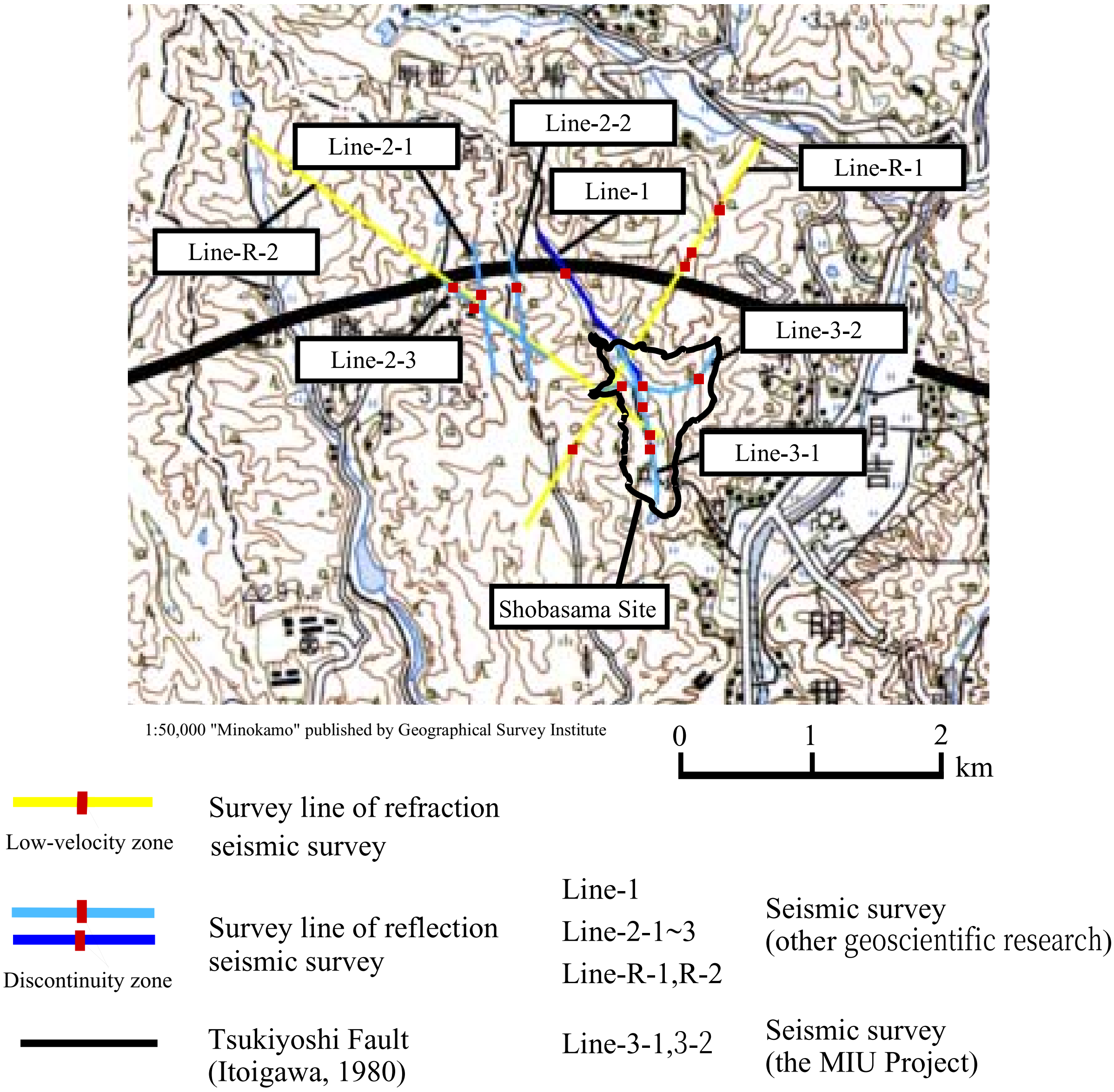

Figure 4.4 Location map of survey lines for seismic survey

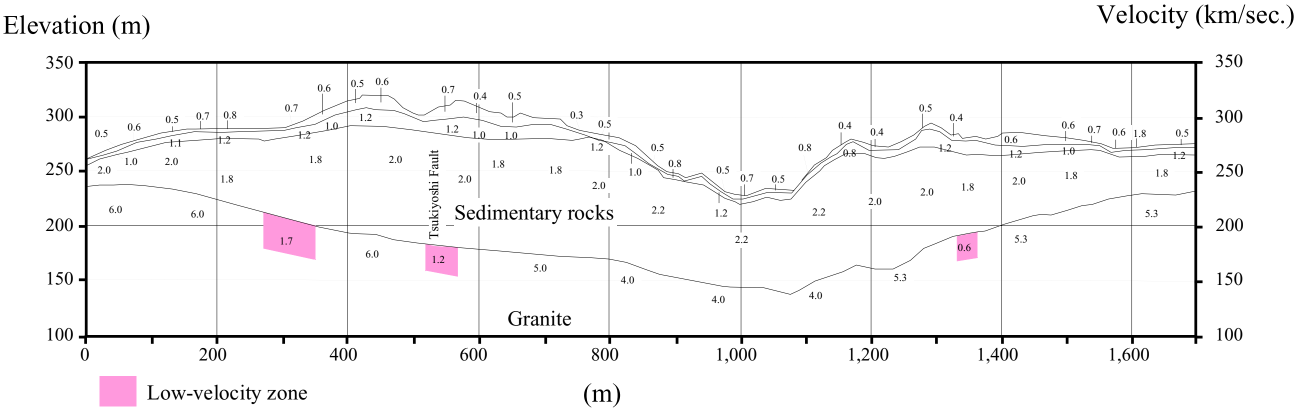

Figure 4.5 Distribution of seismic wave velocity (Line-R-1) [15]

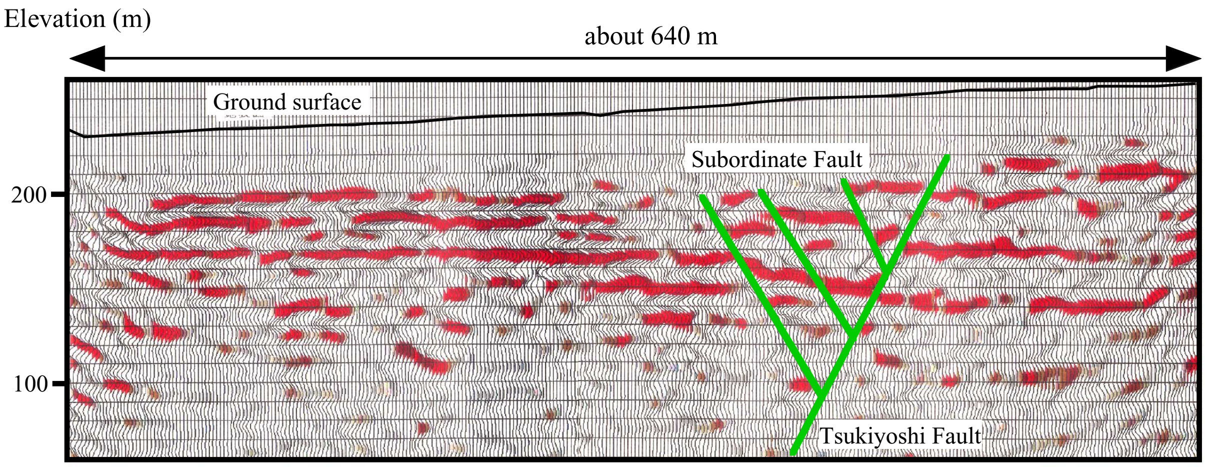

Figure 4.6 Cross section of survey line A-B (Line-1) [15]

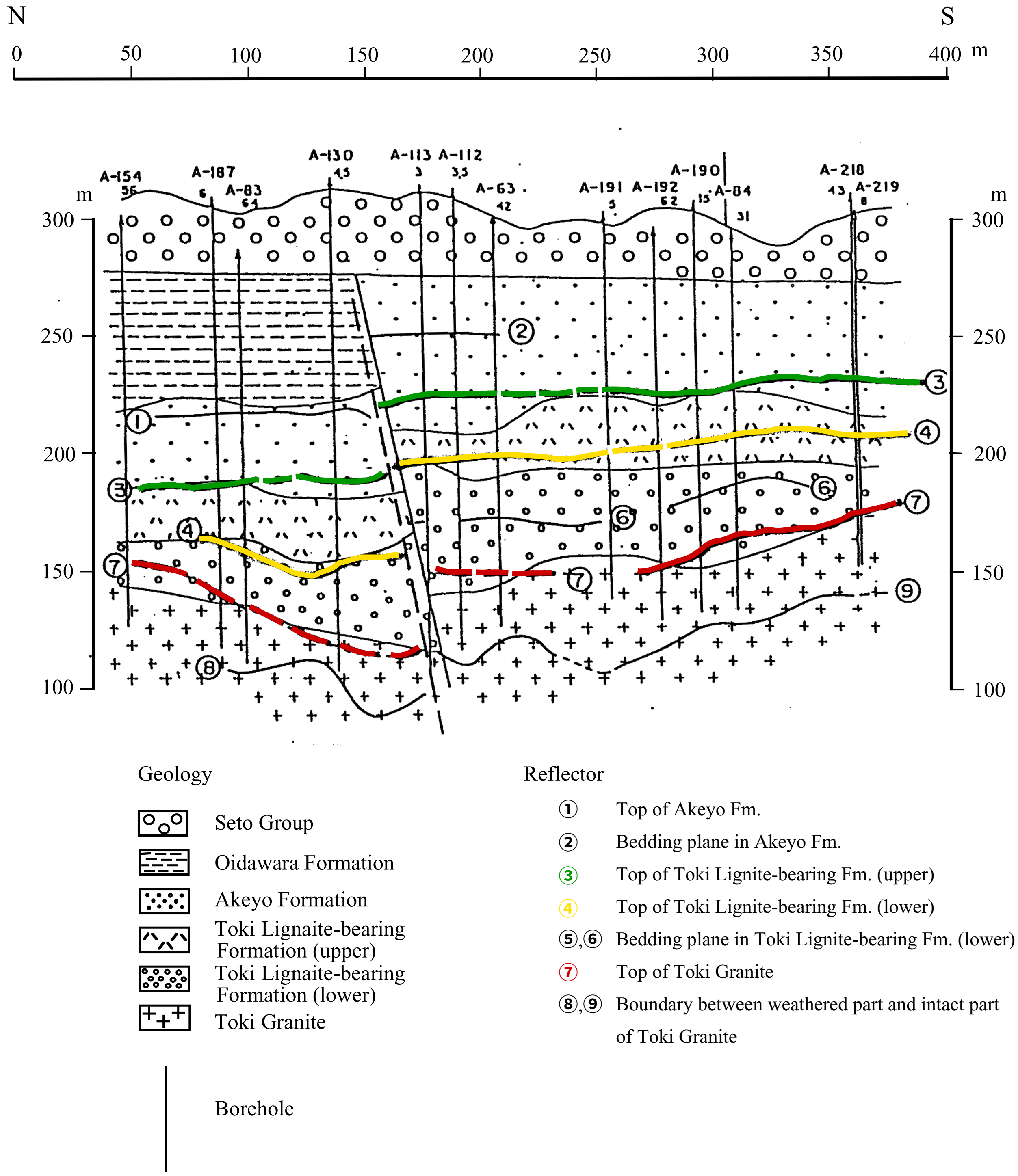

Figure 4.7 Distribution of reflectors obtained by reflection seismic survey

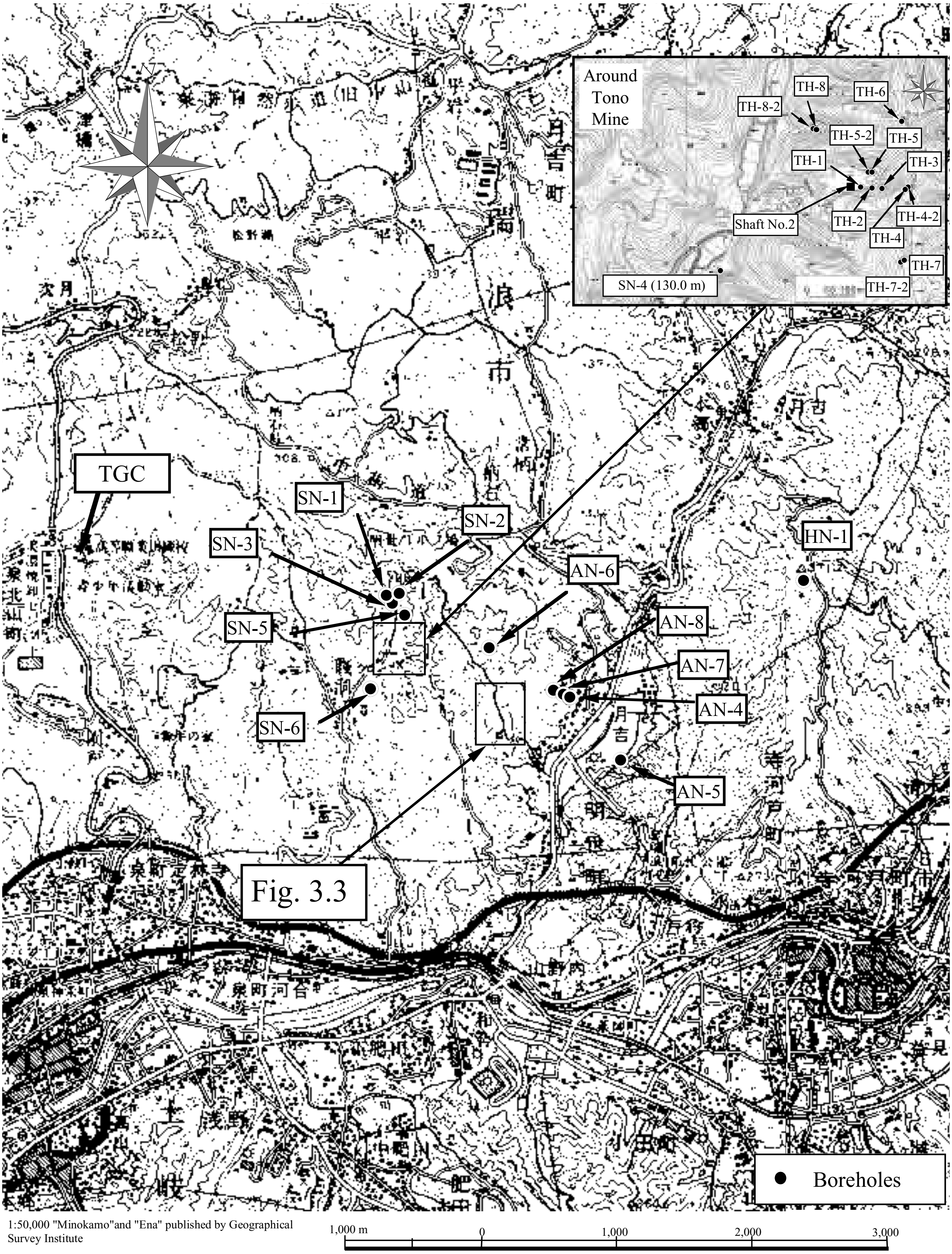

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Figure 4.8 Location map of boreholes for the geoscientific research

Table 4.6 Details of borehole investigations (AN-1, 3)

	AN-1	AN-3
Depth (m)	1,000	408
Diameter	HQ (about 100 mm)	HQ (about 100 mm)
Drilling fluid	Fresh water	Fresh water
Geophysical logging*	○	○
BTV investigations	○	○
In-hole hydraulic test	(33 intervals)	(24 intervals)
Laboratory tests using rock specimen	Apparent density (20 samples) Effective porosity (20 samples) Water content (20 samples) Seismic wave velocity (20 samples) Uniaxial compression test (20 samples) Brazilian test (40 samples)	—
Hydraulic fracturing test	(20 samples)	—

* : Electrical, Micro resistivity, Density, Neutron, Gamma-ray, Acoustic, Temperature, Caliper and Deviation

4.1.3 Geological results - results of Phase I-a

Phase I-a includes the work for the MIU Project at the Shobasama Site. This includes the entire borehole drilling at the site in the reporting period (1996-1999), all the multi-disciplinary borehole investigations and any surface investigations such as the geophysical surveying. Lastly, it includes any modeling based on the new information developed in the period.

In Phase I-a, EM magnetotelluric and reflection seismic surveys were done, three boreholes were drilled (MIU-1, 2 and 3, Table 3.2) and multidisciplinary borehole investigations were carried out at the Shobasama Site. Based on the results of these investigations, a revised geological model was constructed. Details of the investigations are as follows.

4.1.3.1 Magnetotelluric survey

A resistivity survey was carried out at the Shobasama Site (survey line: N-S, 200 m, Table 3.1). However, accurate results were not obtained because of the low-resistivity zone in the near-surface part of the site. Also, application testing of a remote-reference method in magneto electric survey (MT) was carried out aiming at understanding the geological structure in deeper parts of the site. The remote- reference method takes advantage of high coherency of MT signal compared with that of regional noise. By comparing the measurement data at two locations, the MT signal can be separated from the regional noise. Unfortunately, reliable data was not obtained because of excessively high noise levels. Thus the results of these surveys are not presented in this report.

4.1.3.2 Reflection seismic survey [37,38]

A reflection seismic survey was carried out to obtain data on geological structures of Mizunami Group and the depth and geometry of unconformity between the basal conglomerate and the Toki granite. Survey lines were run N-S and E-W and are shown in Figures 4.4 and 4.9. These data are used to construct the geological model. Details of the reflection seismic survey are shown in Table 4.7.