Evolution of a volcanic edifice in the Izu-Ogasawara (Bonin) arc : Lithological characteristics of a 1500 meter core sample in Hachijojima

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Abstract. Lithological characteristics are described for a 1500 meter drilled core sample recovered by NEDO (New Energy and Industrial Technology Development Organization, Japan) at the Site N2-HJ-4 in the central crater of the Higashiyama Volcano, Hachijojima, Izu-Ogasawara (Bonin) arc. The core sample is divided into three main units (Unit I, II and III) based on lithological characteristics. Unit I (32-690 meter in drilling depth) is mainly composed of basaltic lavas and pyroclastic materials which are interpreted to represent rocks of volcanic edifices of the Higashiyama Volcano. Unit II (690-1,062 meter in drilling depth) consists of basaltic and doleritic rocks and hyaloclastite. This unit has lithological nature transitional from Unit III to Unit I, and probably represents rocks of a submarine volcanic edifice. Unit III (1,062-1,485 meter in drilling depth) consists dominantly of volcaniclastic sedimentary rocks, including turbidity or rhythmically deposited lithofacies. This unit was probably formed on a submarine flank of a volcanic edifice of unknown age. Parts of Unit III accompany with highly oxidized basaltic lapillis.

Key Words : Higashiyama Volcano, Hachijojima, Izu-Ogasawara arc, drilled core sample, volcanic edifice.

Introduction

The Izu-Ogasawara arc has been formed at the eastern margin of the Philippine Sea Plate as the result of subduction of the Pacific Plate. The arc consists of an active volcanic chain and backarc rift basin system superimposed on Tertiary volcanic chains and other old crustal structures. Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and other marine geological surveys advanced our understanding of this arc system (cf. Taylor and Natland, 1995).

Hachijojima is located on the volcanic front of Izu-Ogasawara arc, and is mainly composed of two stratovolcanoes, the Nishiyama and Higashiyama Volcano (Fig. 1). General geology of Hachijojima was descried by Isshiki (1959). As shown in Fig. 1, the Higashiyama Volcano comprises several volcanic edifices including the main stratovolcano, central pyroclastic cones and other old edifices (Isshiki, 1959 ; Tsukui et al., 1991 ; 1993 ; Suga, 1991 ; 1993 ; 1994 ; 1996). Tsukui et al. (1991) clarified eruptive history of the main stratovolcano during last 22,000 years, and Tsukui et al. (1993) discussed the evolution of magma plumbing system of this volcano over the last 30,000 years. Volcanic activity of the main stratovolcano probably started about thirty thousands years ago on the old edifices (Suga, 1994 ; 1996). K-Ar age of <0.14Ma was obtained from one of the old edifices (Kaneoka et al., 1970). The Nishiyama Volcano, another stratovolcano in Hachijojima, has been active since 10,000 B.P. (Tsukui et al., 1991).

Notsu et al. (1983) and Onuma et al. (1983) discussed geochemical characteristics of volcanic rocks from Hachijojima and other volcanic islands of the Izu volcanic chain. Rocks of the Higashiyama Volcano range widely from basaltic to dacitic composition, while the Nishiyama Volcano is composed dominantly of basaltic lavas and pyroclastic materials of the low-potassium tholeiitic basaltic composition (Isshiki, 1959 ; Tsukui et al. 1993).

NEDO drilled at eight sites in Hachijojima for geothermal development promotion survey in 1989-1991. Contents of this drilling survey were minutely reported by NEDO (1993). Chemical compositions of selected rock samples recovered at the all drilling sites were reported by Nakano et al. (1993).

This note describes lithological characteristics of one of the NEDO core samples ; a 1,500 meter drilled core sample recovered at the Site N 2 -HJ- 4 (altitude 567 meter) in the central crater of the Higashiyama Volcano (Fig. 1). This 1,500 meter core sample with remarkable recovering rate will provide essential data set for better understanding of the evolution of a volcanic edifice located on the volcanic front of Izu-Ogasawara arc.

The core sample studied in this note is a registered rock

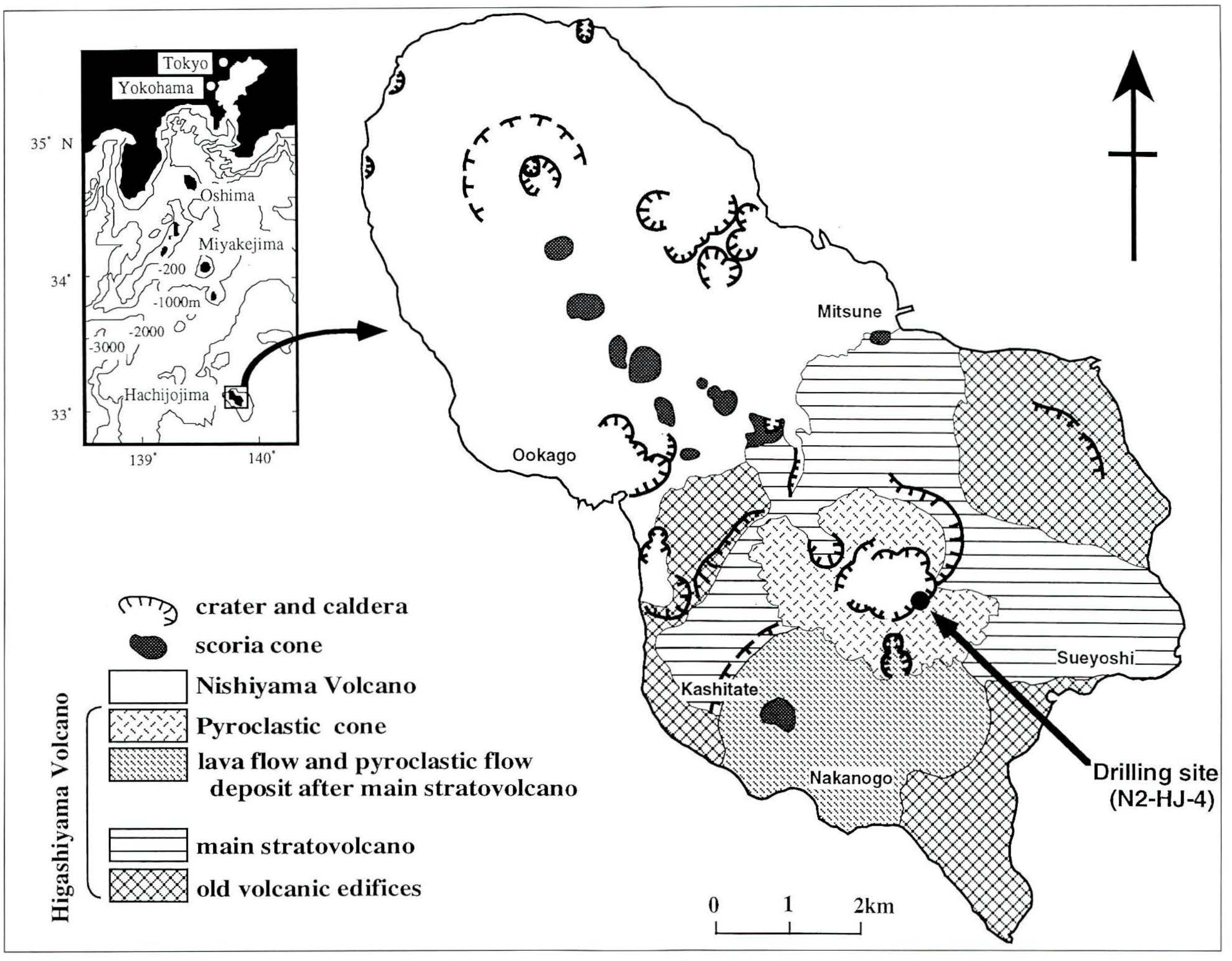


Fig. 1. Geological outline of Hachijojima. (modified after Suga et al, in preparation)

specimen (Registered Number : KPM-NO0000001) of the Kanagawa Prefectural Museum of Natural History (KPMNH) and the sample information is available from the KPMNH upon request.

Lithological description of the core sample

On the basis of the lithological characteristics, the core sample N2-HJ-4 is divided into three main units (Unit I, II and III), and further subdivided into 19 sub-units (Fig. 2). Detailed litholofacies variation and petrographic features of the core sample are given in Appendix 1 and 2 respectively.

Unit I : Volcanic edifice of Higashiyama Volcano

Unit I (32-690 meter : hereinafter meter drilling depth) is mainly composed of basaltic lavas and pyroclastic materials which are interpreted to represent rocks of volcanic edifices of the Higashiyama.

Unit I-a (32-115 meter) consists of basaltic andesitic lava (Fig. 3-1) which is characterized by megacrysts of plagioclase (as much as 1 centimeter in diameter) and glomeroporphyritic clots of coarse grained plagioclase and olivine. They are probably xenocrystic origin (cf. Arakawa & Kimata, 1992). Unit-b (115-176 meter) is weakly welded coarse grained ash including lapilli. Unit I-c (176-367 meter) is composed of welded spatter and scoria with lava (Fig. 3-2). Strongly welded spatter of Unit I-d (367-435 meter) shows remarkable eutaxitic texture (Fig. 3-3). Unit I-e (435-470 meter) consists of volcaniclastic material and lava blocks. Rocks of unit I-b, I-c, I-d and I-e were badly altered and brecciated and became sandy appearance. Unit I-f (470-605 meter) comprises variably altered basaltic subaerial lavas. Each lava is 2 to 10 meter thick in this unit (Fig. 3-4). Clinkers in this unit were extensively altered and brecciated. Unit I-g (605-690 meter) comprises weakly altered andesitic or basaltic subaerial lavas. Each lava unit is 10 to 30 meter in thickness.

Unit II : Transitional zone

Unit II (690-1062 meter) consists of basaltic and doleritic rocks, and hyaloclastite. This unit has lithological characteristics transitional from Unit III to Unit I.

Unit II-a (690-710 meter) is an accumulation of partly brecciated, cracky and glassy basaltic rocks of 2 to 3 meter in thickness. Basaltic intrusive rock of Unit II-b (710-780 meter) contains variable lithofacies including doleritic rock fragments, clots of plagioclase, and andesitic to dacitic xenoliths (Figs. 3-5, 3-6). Unit II-c (780-935 meter) consists dominantly of doleritic intrusive rocks (Fig. 3-7).

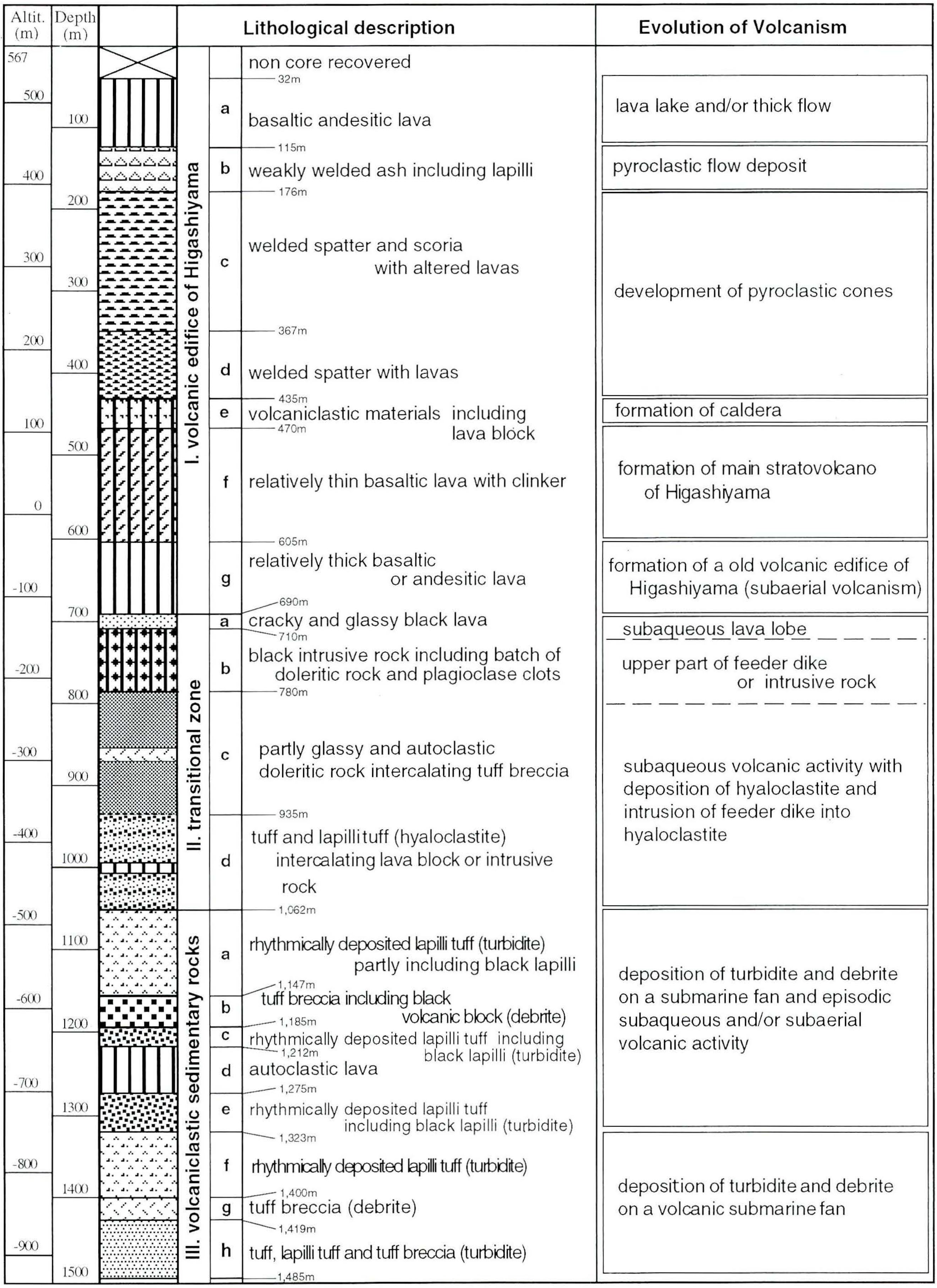
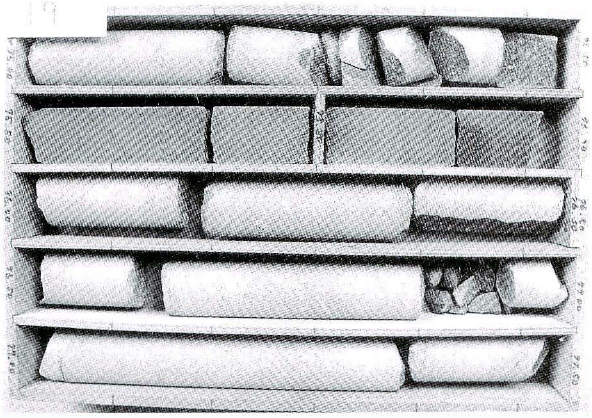
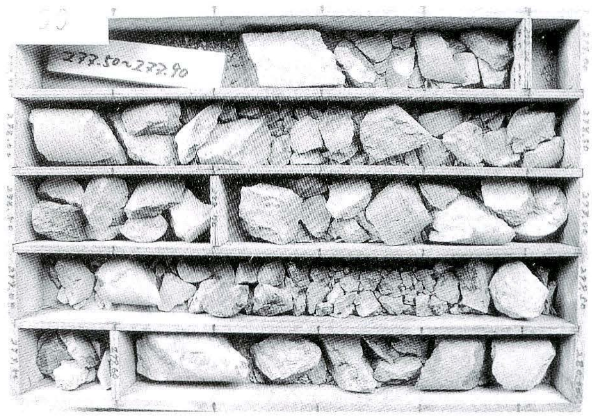


Fig. 2. Summary of lithological variation of the Site N 2 -HJ- 4 core sample

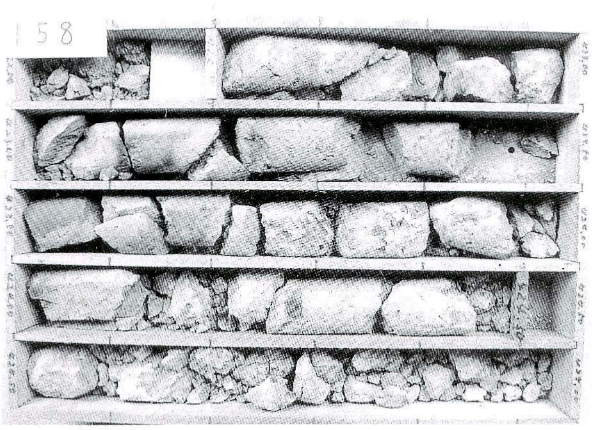
Fig. 3. Photographs of the core sample. Drilling depth is given in parenthese.



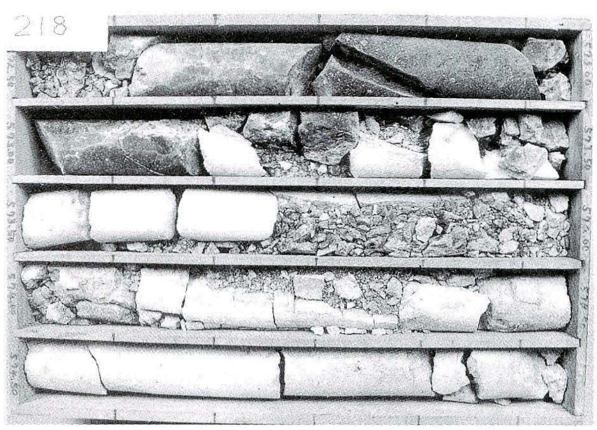
3-1. basaltic andesitic lava (box no. 19, 75 - 77.5 meter)



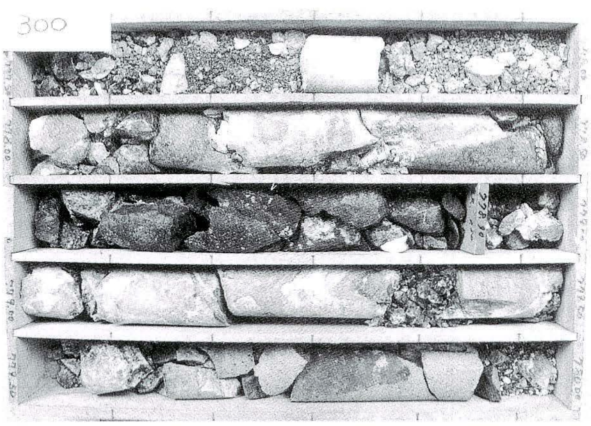
3-2. brecciated and altered basaltic lava (box no. 100, 277.5 - 280 meter)



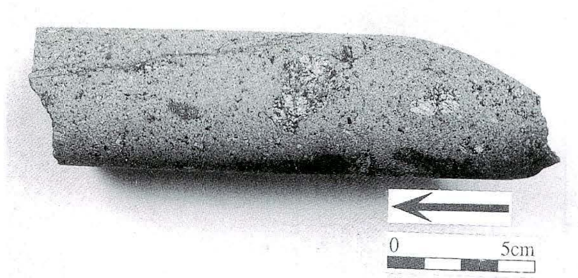
3-3. altered spatter (box no. 158, 422.5 - 425 meter)



3-4. altered basaltic or andesitic lava (box no. 218, 572.5 - 575 meter)

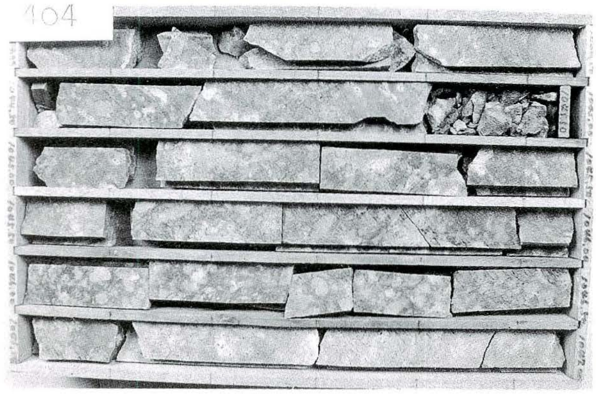


3-5. altered basaltic intrusive rock (box no. 300, 777.5 - 780 meter)

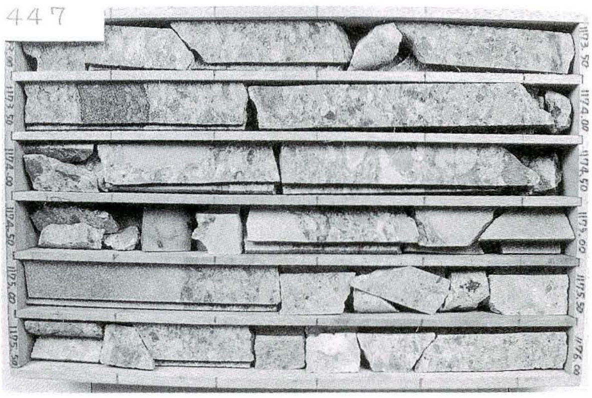


3-6. basaltic rock including clot of plagioclase (box no. 280, 727.5 - 730 meter)

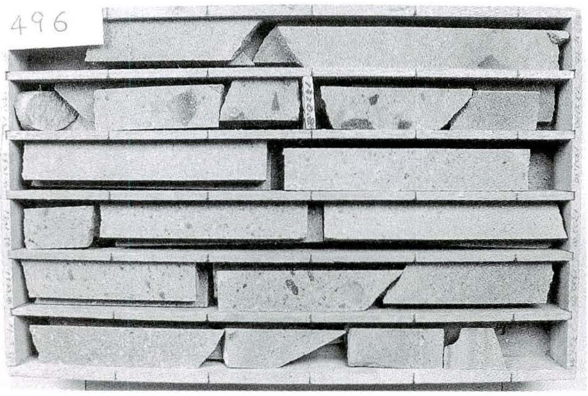
3-7. doleritic intrusive rock (box no. 349, 900 - 902. 5 meter)



3-8. glassy tuff (hyaloclastite) (box no. 404, 1,044 - 1,047 meter)



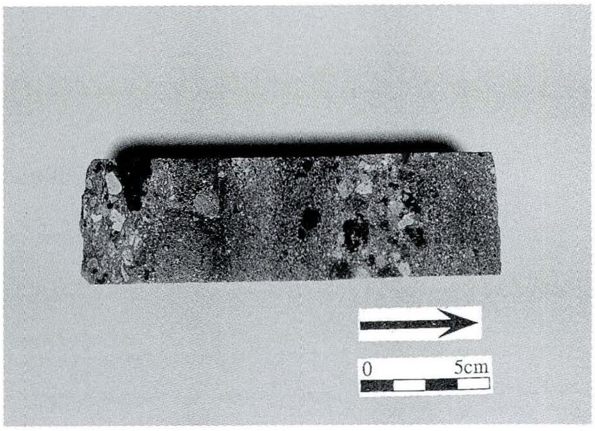
3-9. tuff breccia including black volcanic block (box no. 447, 1, 173 - 1, 176 meter)



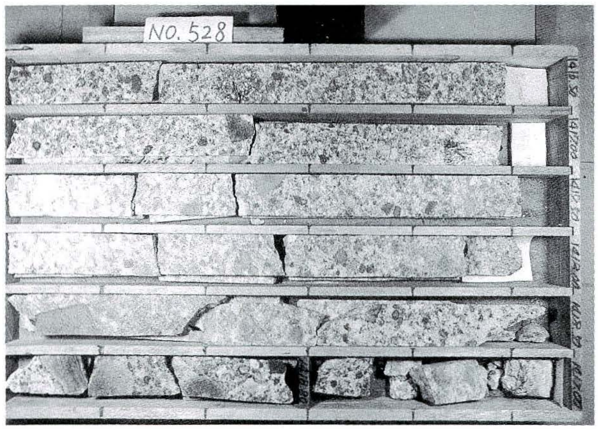
3-10. rhythmically deposited lapilli tuff (turbidite) including black volcanic lapilli (box no. 496, 1,320 - 1,323 meter)

3-11. submarine autoclastic lava (box no. 476, 1,260 - 1,263 meter)

3-12. rhythmically deposited lapilli tuff (turbidite) (box no. 509, 1,359 - 1,362 meter)

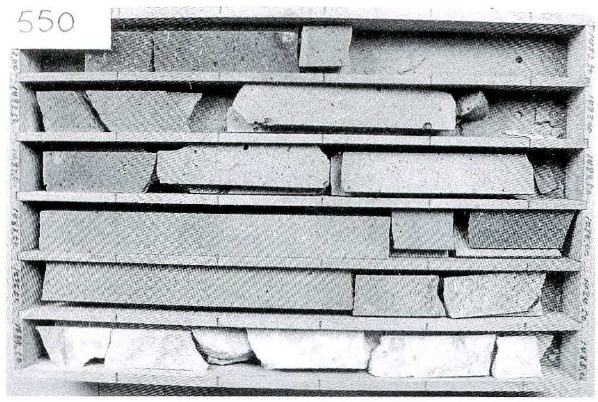


3-13. close up of rhythmically deposited lapilli tuff (turbidite) (box no. 509, 1,359.3 meter)



3-14. tuff breccia (debrite) (box no. 528, 1,416 - 1,417 meter)

3-15. tuff and lapilli tuff (turbidite) (box no. 542, 1,458 - 1,461 meter)



3-16. andesitic intrusive rock (box no. 550, 1,482 - 1,485 meter)

An upper part of this unit is composed of rocks of glassy appearance, showing water chilled structure. This glassy basaltic rock is interpreted as a cooling facies of the doleritic intrusive rock. Unit II-d (935-1,062 meter) consists of hydrothermally altered glassy tuff and lapilli tuff (Fig. 3-8) intercalated with thin basaltic intrusive rocks and/or lava blocks.

Unit III : Volcaniclastic sedimentary rocks.

Unit III (1,062-1,485 meter) dominantly consists of volcaniclastic sedimentary rocks. Rocks of this unit are turbidly or rhythmically deposited lithofacies. Volcaniclastic rocks in Unit III have been hydrothermally altered. They are greenish or bleached rocks owing to the degree and nature of hydrothermal alteration processes.

Unit III-a (1,062-1,147 meter) consists of rhythmically deposited and graded bedded lapilli tuff partly including black lapillis. Each graded bed is usually 1 to 5 meter (often maximum 12 meter) in thickness. Tuff breccia of Unit III-b (1,147-1,185 meter) includes black volcanic blocks, some of which were oxidized and rounded in shape (Fig. 3-9). Lapilli tuff beds of Unit III-c and Unit III-e (1,185-1,212 and 1,275-1,323 meter) exhibit the graded bedding structure as well as the rhythmic deposition structure. This unit includes black lapillis (Fig. 3-10). Each graded bed is 2 to 5 meter thick. Unit III-c and Unit III-e are interbedded with subaqueous autoclastic lava of Unit III-d (1,212-1,275 meter) (Fig. 3-11). Unit III-f (1,323-1,400 meter) consists of rhythmically deposited lapilli tuff and tuff layers (Figs. 3-12, 3-13). Each depositional cycle is defined by alternation of lapilli tuff and tuff layers, and one depositional cycle is 2 to 10, or locally several tens of centimeter in thickness. Between depositional cycles, various textures indicative of frequent erosional events are noted. Unit III-g (1,400-1,419 meter) is a massive tuff breccia (Fig. 3-14) including red-colored oxidized lapillis. Unit III-h (1,419-1,485 meter) comprises tuff, lapilli tuff, tuff breccia (Fig. 3-15) and basaltic and andesitic intrusive rocks (Fig. 3-16).

Discussion

The nature and variation of the lithofacies of Unit I-a to Unit I-g are well comparable to the volcanic edifice of the main stratovolcano (Suga, in preparation). The basaltic andesitic lava of Unit I-a is interpreted to represent a thick lava flow and/or lava lake. The pyroclastic materials of Unit I-b are probably pyroclastic flow deposits. The welded spatter and scoria of Unit I-c and I-d are lithologically equivalent to the central pyroclastic cones of the main stratovolcano (Suga, 1996). Welded spatter and scoria in the Unit I-c probably erupted at the latest stage of development of the central pyroclastic cones. Volcaniclastic materials in the Unit I-e represent caldera deposits. Relatively thin basaltic lavas in the Unit I-f correspond to the rocks of the main stratovolcano. Relatively thick andesitic lavas in the Unit I-g represent materials of an old edifice of the Higashiyama Volcano.

The pyroclastic materials and highly vesiculated basaltic lavas in the Units I-b, I-c, I-d, I-e, and I-f were highly altered while relatively lower degree of alteration is noted in the massive lava rocks in the Units I-a and I-g. These features suggest that degree of alteration was strongly related to porosity of rocks. Parts of the Unit I with loose sandy appearance seem to represent highly porous loose pyroclastic and/or volcaniclastic materials.

The transitional zone (Unit II) comprises an accumulation of cracky and glassy basaltic rocks (Unit II-a), glassy basaltic intrusive rocks with doleritic rock fragments (Unit II-b), doleritic intrusive rock and its cooling facies with water chilled structure (Unit II-c), and glassy tuffs (Unit II-d). These lithofacies are interpreted as subaqueous lava lobe, upper part of feeder dike or other intrusive rock, feeder dike which intruded into hyaloclastite, and hyaloclastite respectively. The transitional zone seems to represent a submarine volcanic edifice, but it is not clear whether the submarine edifice was formed under submarine eruption stage of the Higashiyama Volcano or unknown earlier volcano.

Textural features of the volcaniclastic sedimentary rocks in the Units III-a, III-c, III-e, III-f and III-h suggest that they are turbidite. They consist of rhythmically deposited or graded bedded lapilli tuff, tuff, and tuff breccia. The tuff breccia of Unit III-b and III-g seems to be debrite (debris flow deposit). The turbidite and debrite in Unit III were probably deposited on submarine flank of volcanic edifice and formed submarine fan. Black volcanic blocks and lapillis in the Units III-a, III-b, III-c and III-e and lava in the Unit III-d are interpreted to be products of episodic submarine volcanism. Subaerial eruption is suggested for some rocks in the Unit III in which oxidized red-colored and rounded lapillis and blocks occur.

In spite of extensive search under microscope, no micro fossil was recovered from the sedimentary rocks studied. The volcaniclastic sedimentary rocks in Unit III as a whole are greenish or whitish in color owing to the degree of hydrothermal alteration. The lithological features of the volcaniclastic sedimentary rocks of Unit III suggest that they were products of volcanoes which was active prior to the formation of the main stratovolcano of Higashiyama. As age data is not available, it is not clear whether this earlier volcanic activity was related to that of the old edifices of the Higashiyama Volcano or much older volcano of unknown age. It may be pertinent to mention here that similar lithological features to Unit III have been reported from Tertiary volcaniclastic sedimentary rocks occurring elsewhere in the Izu-Ogasawara arc. The Unit III rocks are lithologically comparable to rocks of Tertiary Yugashima Group or Shirahama Group (Sawamura et al., 1970) in the Izu Peninsula, a northern part of the Izu-Ogasawara arc.

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We are grateful to NEDO and Hachijo Branch Office of Tokyo Metropolitan Government for offer the Site N2-HJ-4 cored sample. We thank to Dr. K. Fujioka (JAMSTEC) and Mr. S. Umezawa (Umezawa Consultant Co.) for their helpful advice, Prof. K. Kosaka (Nihon Univ.) and Prof. T. Ishii (ORI, Univ. of Tokyo) for help with this work. A part of this study was supported by the research subsidy from Tokyo Geographical Society, Budget for Research of the Kanagawa Prefectural Museum of Natural History, and the Decoding the Earth Evolution Program, Intensified Study Area Program of Ministry of Culture and Education (No. 259, 1995-1997).

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伊豆ー小笠原弧火山島の成長発達史を探る：八丈島東山火山の深層ボーリングコア(N2-HJ-4)岩相記載

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要旨

新エネルギー・産業技術総合開発機構（NEDO）が、八丈島地域の地熱開発促進調査のために八丈島東山山頂火口内のN2-HJ-4地点で掘削した、深層ボーリングコア（掘削全長1500m）の岩相を記載した。

コアの岩相は、上位から東山火山の山体（Unit I：掘削深度32～690m）、漸移帯（Unit II：掘削深度690～1,062m）、火山砕屑性堆積岩（Unit III：掘削深度1,062～1,485m）の3つのUnitに区分でき、さらにそれぞれを7、4、8のsubunitに分けることができる。東山火山の山体に相当するUnit Iは、上位から火砕丘およびその噴出物（I-a～I-d）、カルデラ堆積物（I-e）、東山の主成層火山の溶岩（I-f）、古期山体の溶岩（I-g）からなる。これらの岩石は激しい熱水変質を被っており、岩石の空隙率と熱水変質の強度に強い相関が認められる。漸移帯であるUnit IIは、水中溶岩ローブ（II-a）、ドレライト様岩のフィーダー岩脈とその急冷相（II-b、II-c）、およびハイアロクラスタイト（II-d）で特徴づけられる。コア下部の火山砕屑性堆積岩であるUnit IIIは、主に緑色変質を受けたタービダイト、デブライトと、貫入岩からなる。これらは火山体の裾野の海底扇状地に堆積したものと考えられる。このうち、III-a～III-eの火山礫凝灰岩および凝灰角礫岩には、玄武岩ないし玄武岩質安山岩の火山礫が含まれるほか、水冷破砕を受けた水中溶岩が挟在しており、エピソディックな火山活動が示唆される。この部分にはしばしば酸化した火山岩片や円磨された礫が含まれることから、海面上でも噴火活動がおこっていた可能性が高い。Unit III火山砕屑性堆積岩は、伊豆半島の新第三系湯ヶ島層群、白浜層群に類似した岩相を示す。

今回報告したN2-HJ-4深層ボーリングコアは、地上では確認できない火山体内部や火山島下部の地球科学的情報を包含しており、島弧火山の成長発達史を解明する上で貴重な資料である。このコアを堆積学的、岩石学的、地球化学的に検討することによって、八丈島火山の成長発達史ならびに伊豆ー小笠原弧の火成活動の変遷と地殻成長発達史の解明に有益なデータが得られるであろう。

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Appendix 1 . Lithological variation of the Site N2-HJ-4 core sample

Legend

Graphic symboles for lithologies

spatter

aglutinate

lava

tuff breccia / coarse volcaniclastic conglomerate
(cobble to boulder size)

lapilli tuff / fine volcaniclastic conglomerate
(granule to pebble size)

alternation of coarse tuff and lapilli tuff

coarse tuff / volcaniclastic sandstone

alternation of fine tuff and coarse tuff

fine tuff / volcaniclastic mudstone

volcanic rock (lava / intrusive)

volcanic breccia to tuff breccia (hyaloclastite / autobrecciated lava)

lapilli tuff (hyaloclastite / autobrecciated lava)

doleritic rock

sandy disturbance

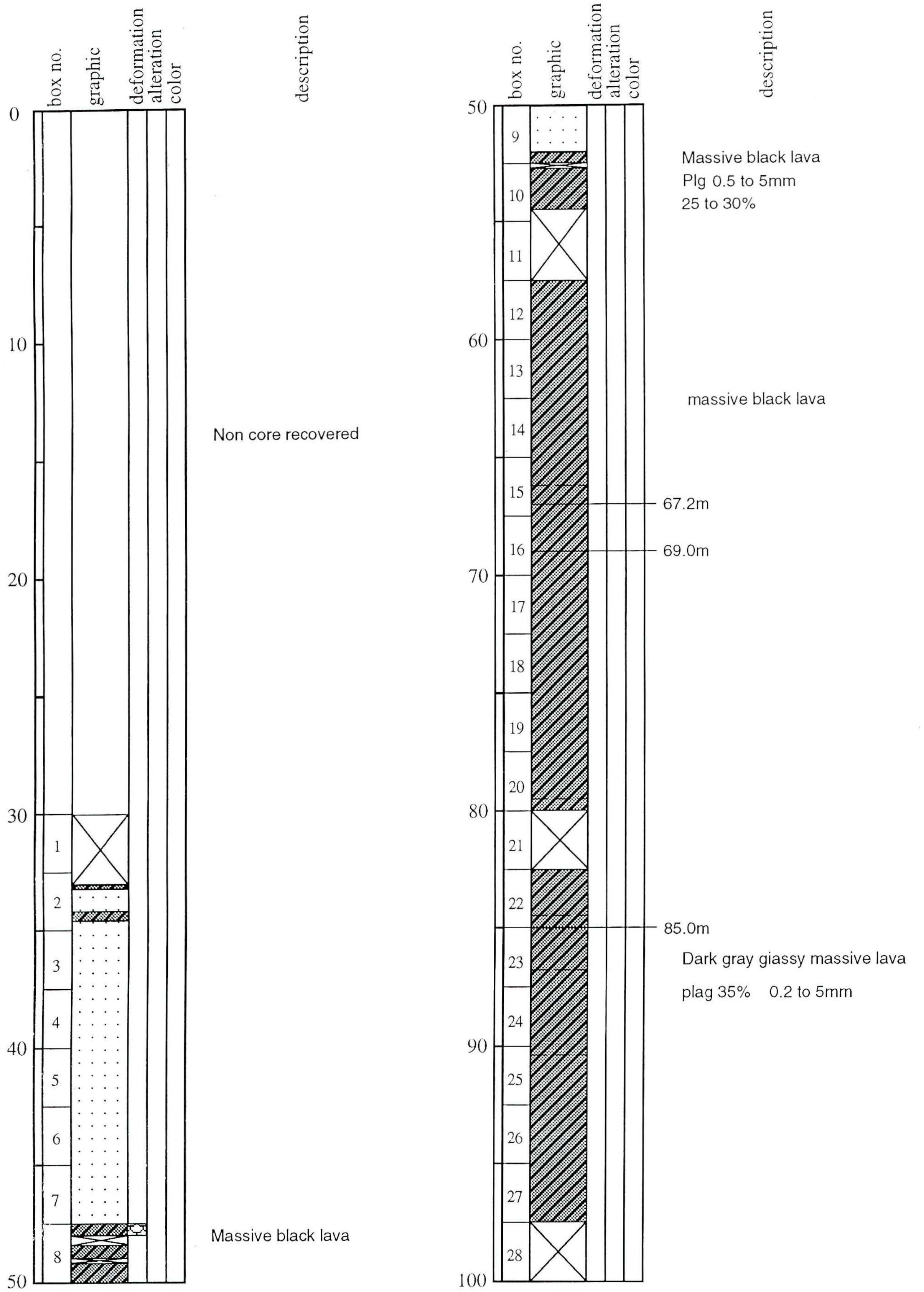
fractured

altered

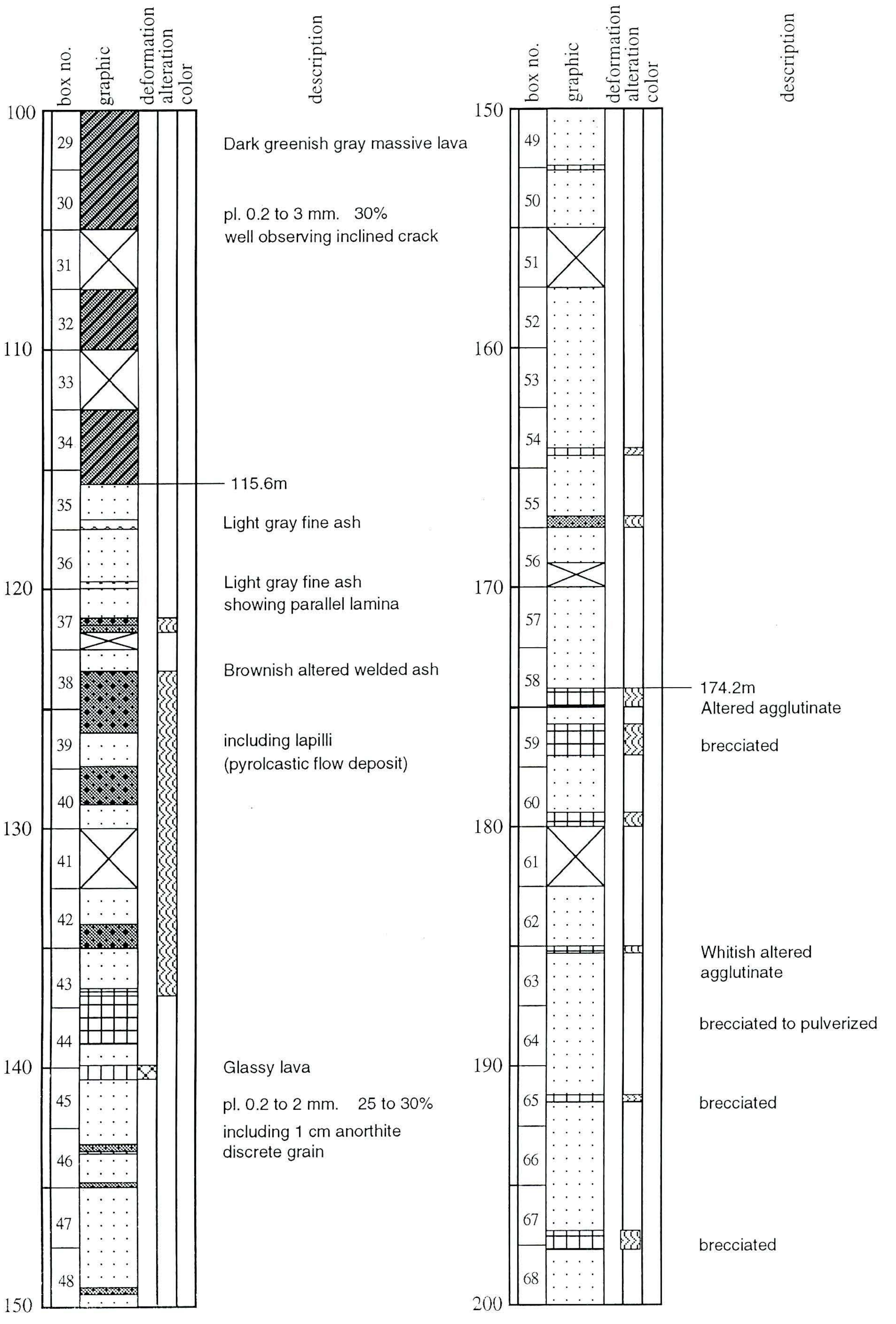
Colors

lgt = light; drk = dark; dp = deep;
wht = white / whitish; gry = grey / greyish;
blk = black / blackish; blu = blue / bluish;
grn = green / greenish; ylw = yellow / yellowish;
brn = brown / brownish

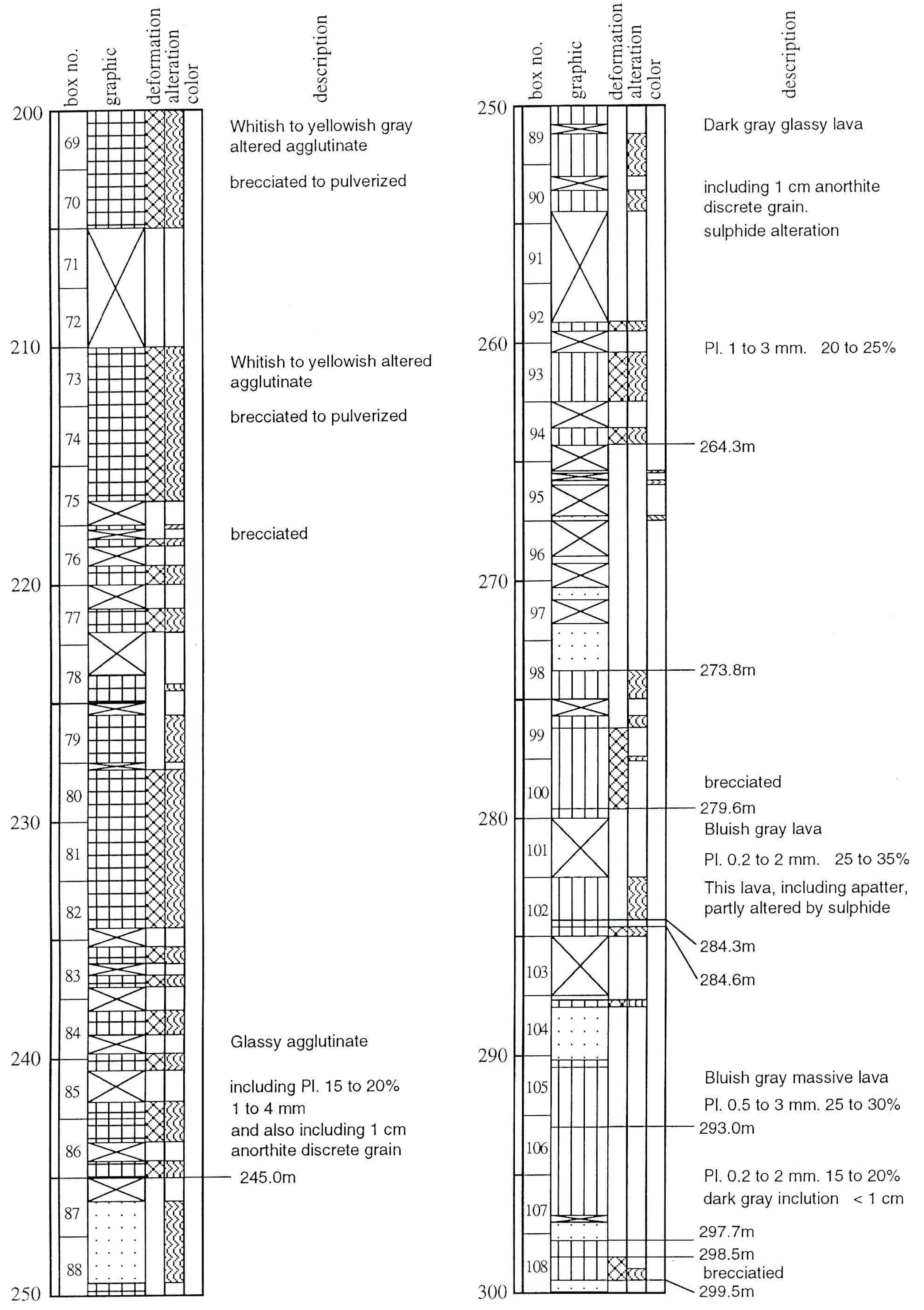
Drilling depth 0-100 m



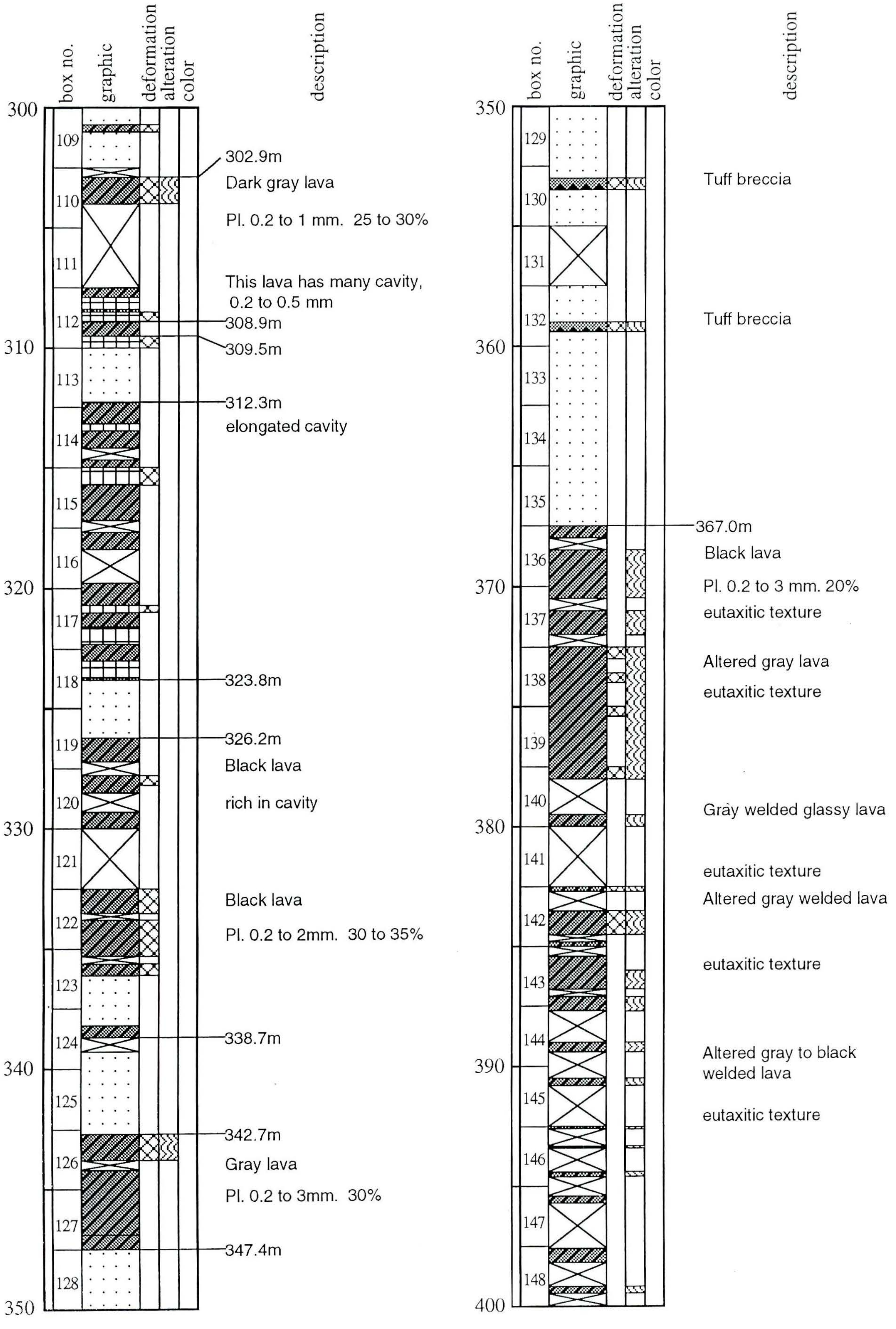
Drilling depth 100-200 m



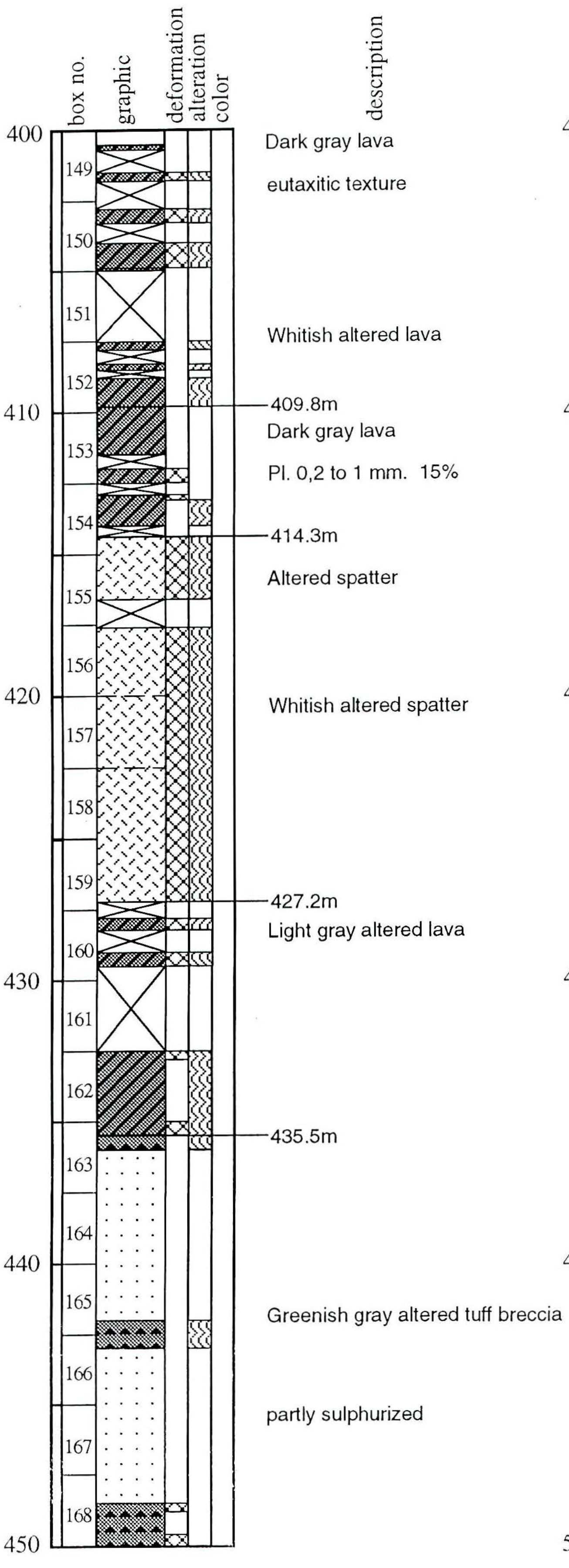
Drilling depth 200-300 m

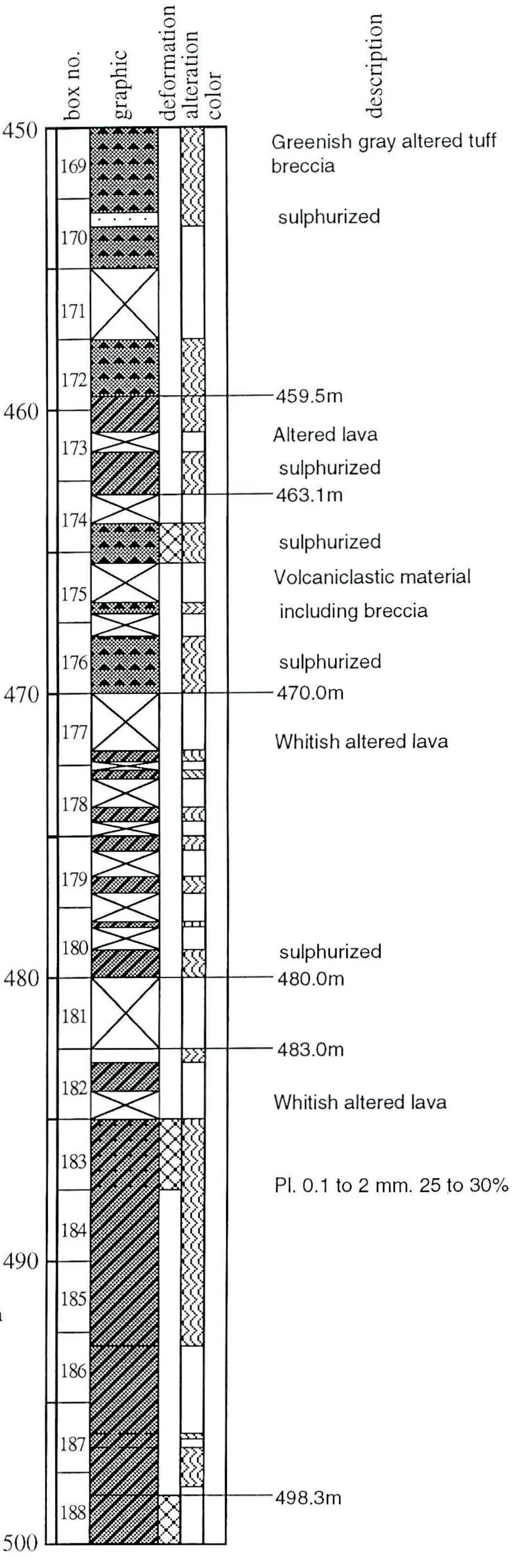


Drilling depth 300-400 m

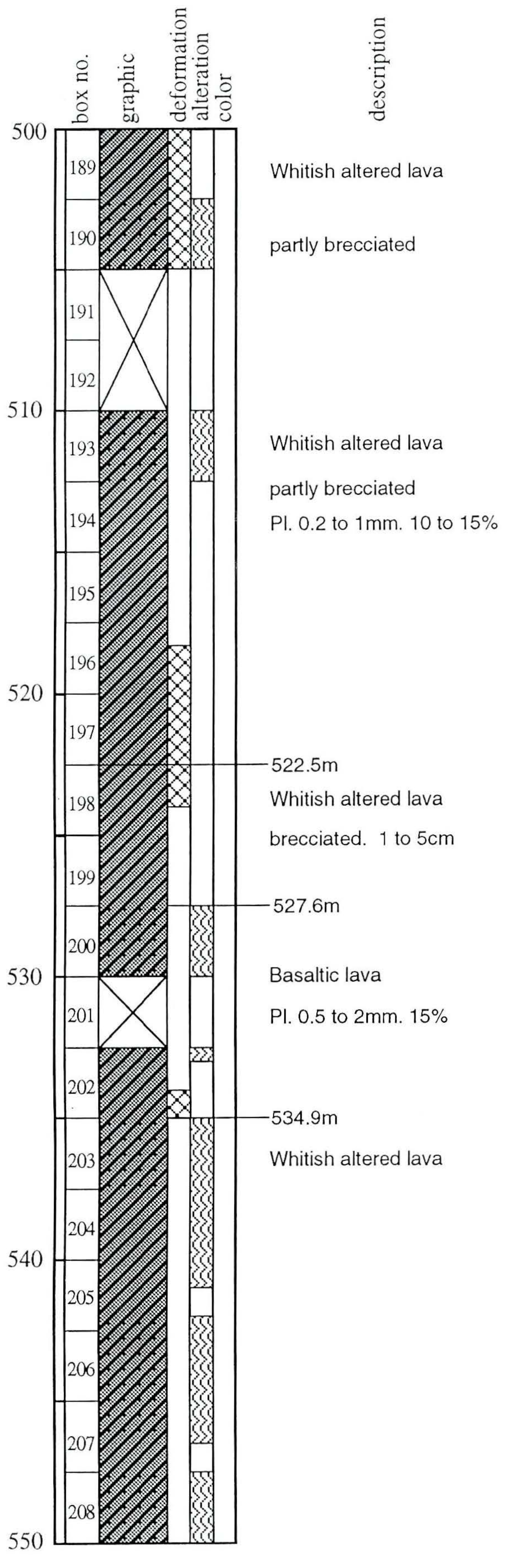


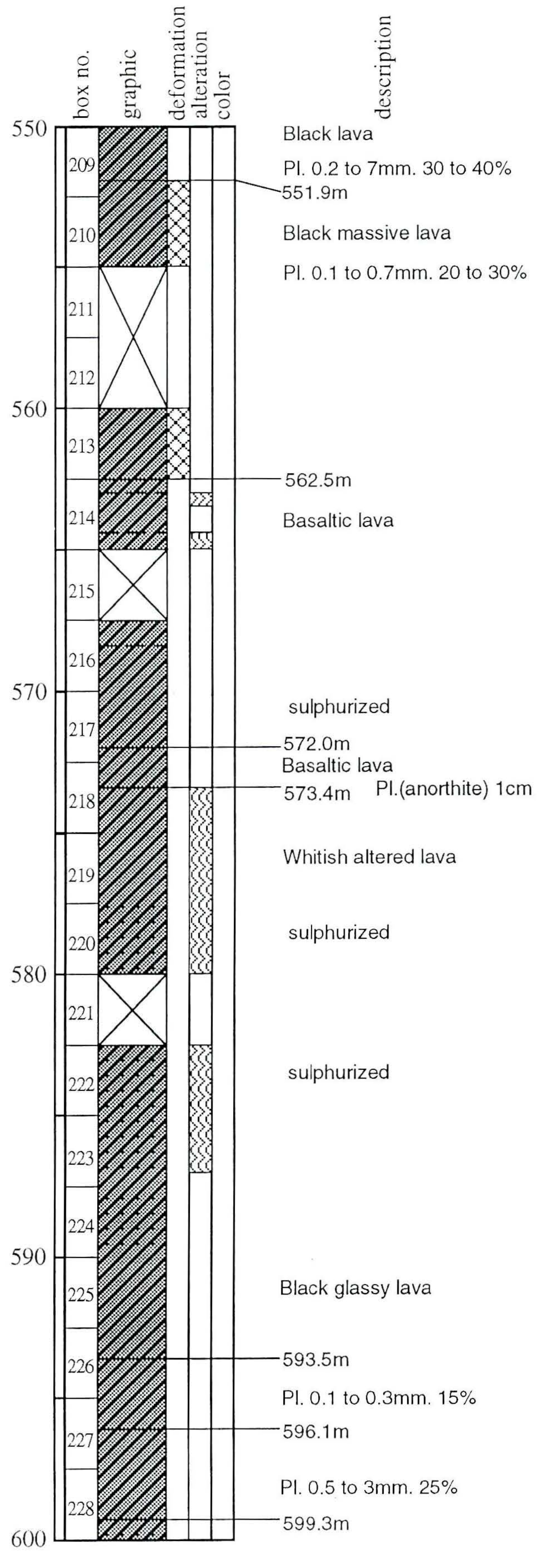
Drilling depth 400-500 m



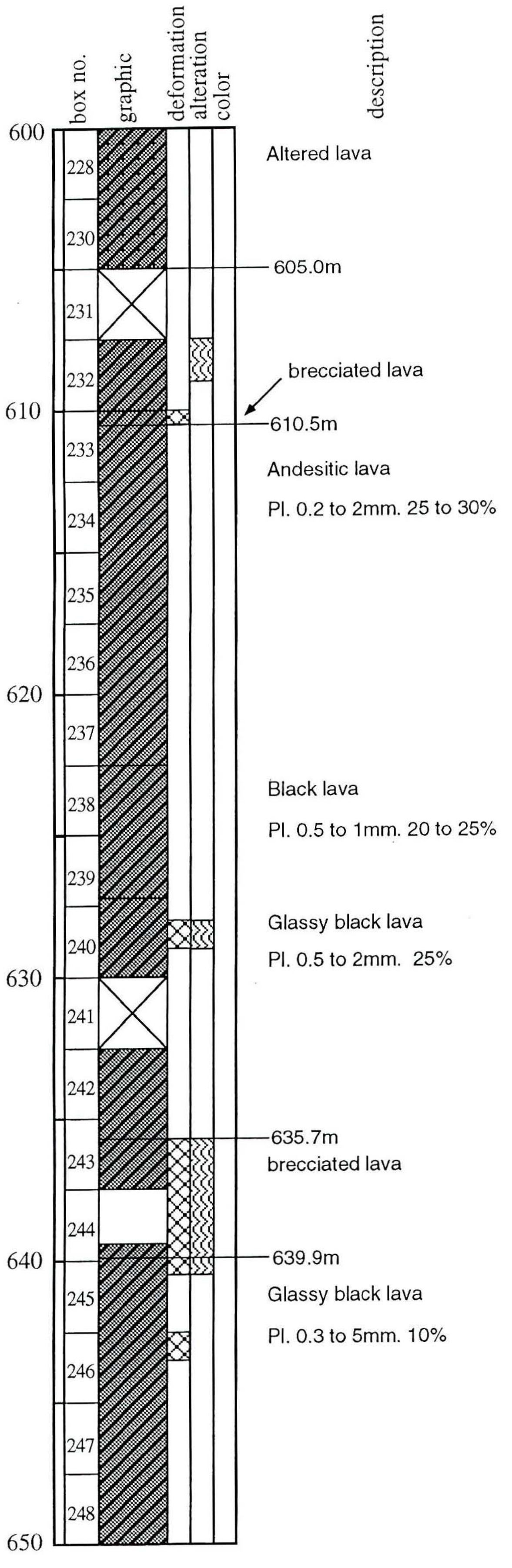


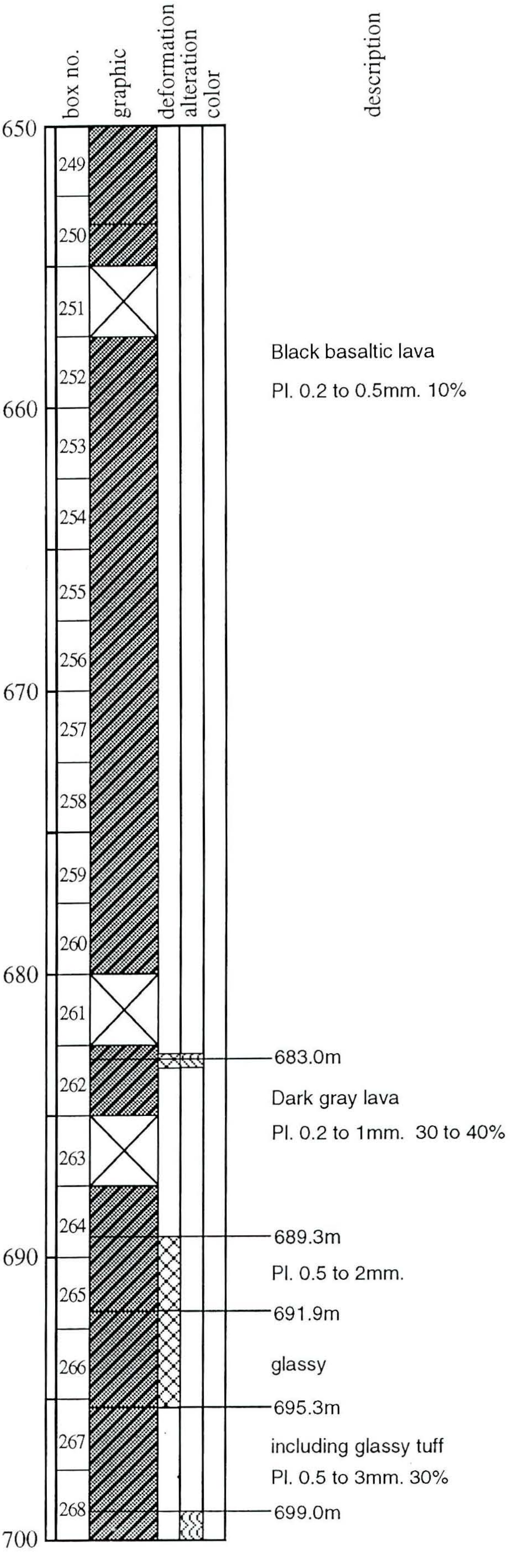
Drilling depth 500-600 m



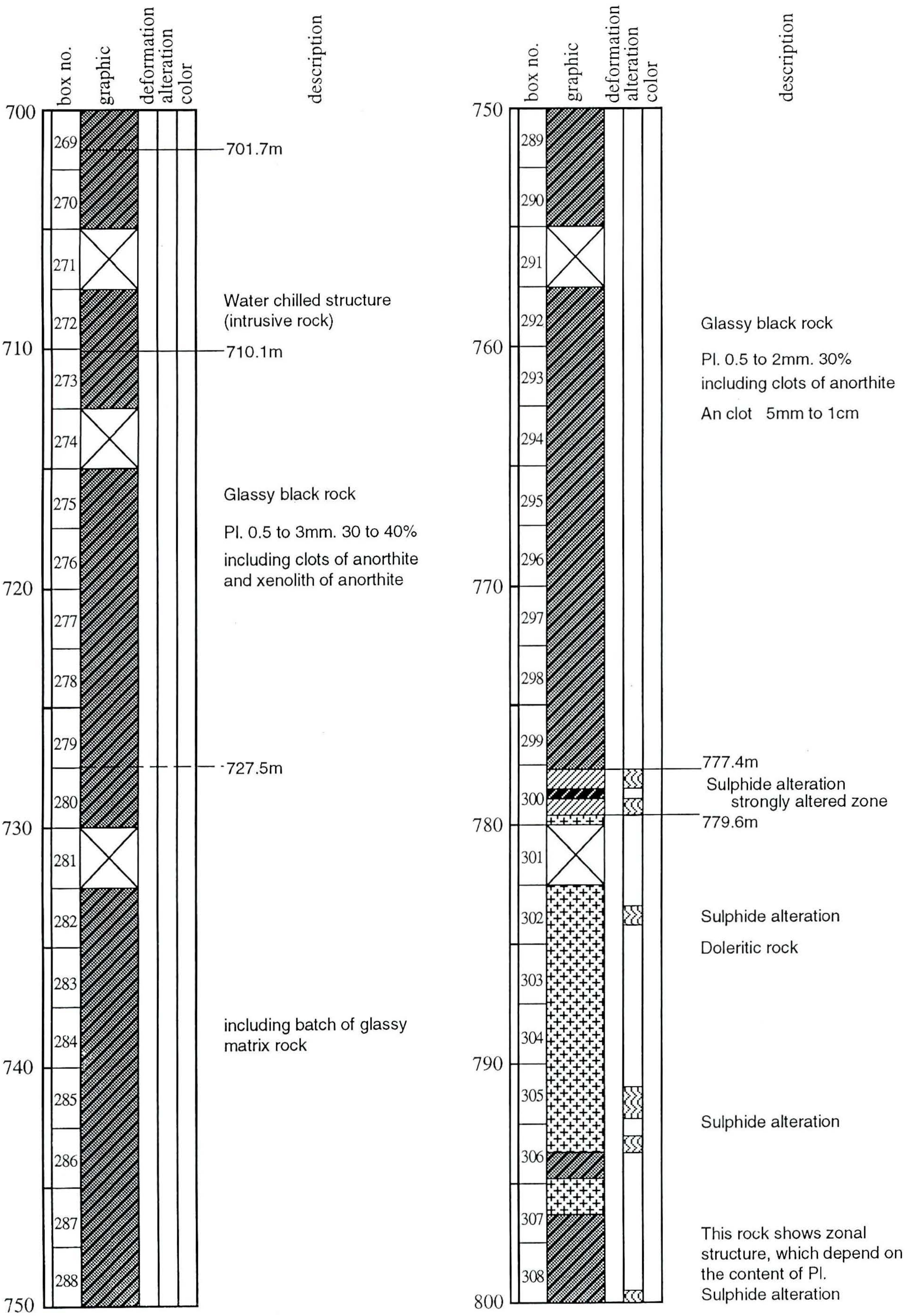


Drilling depth 600-700 m

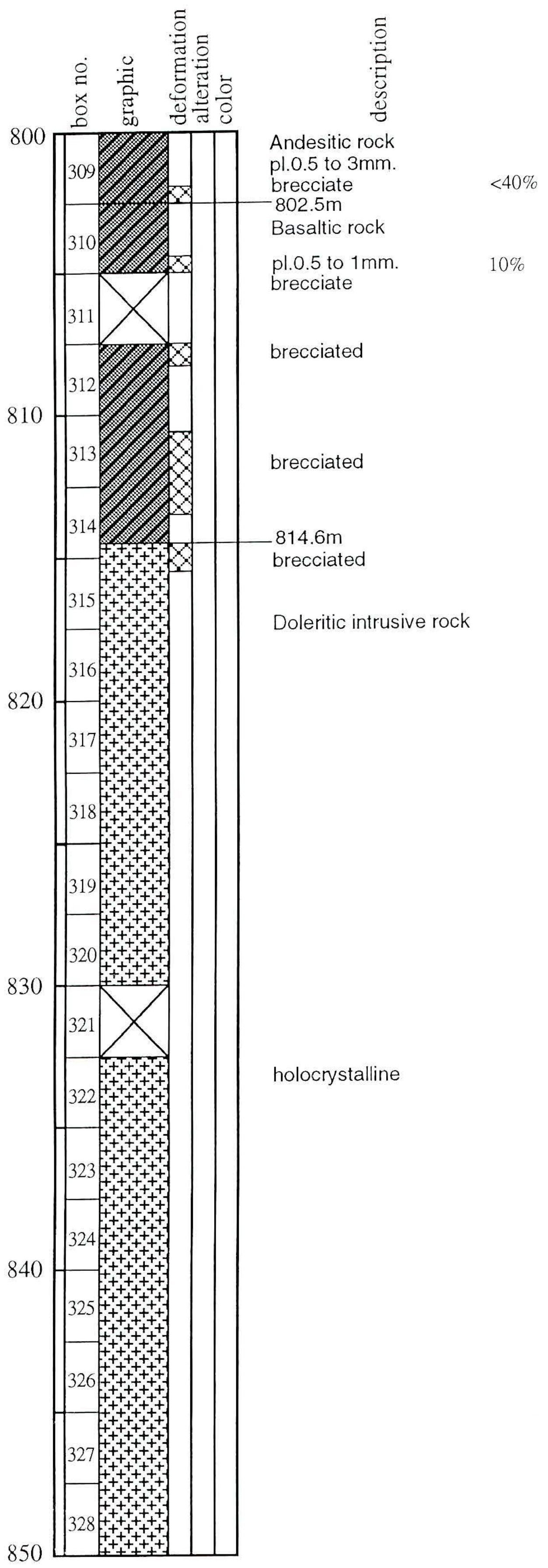


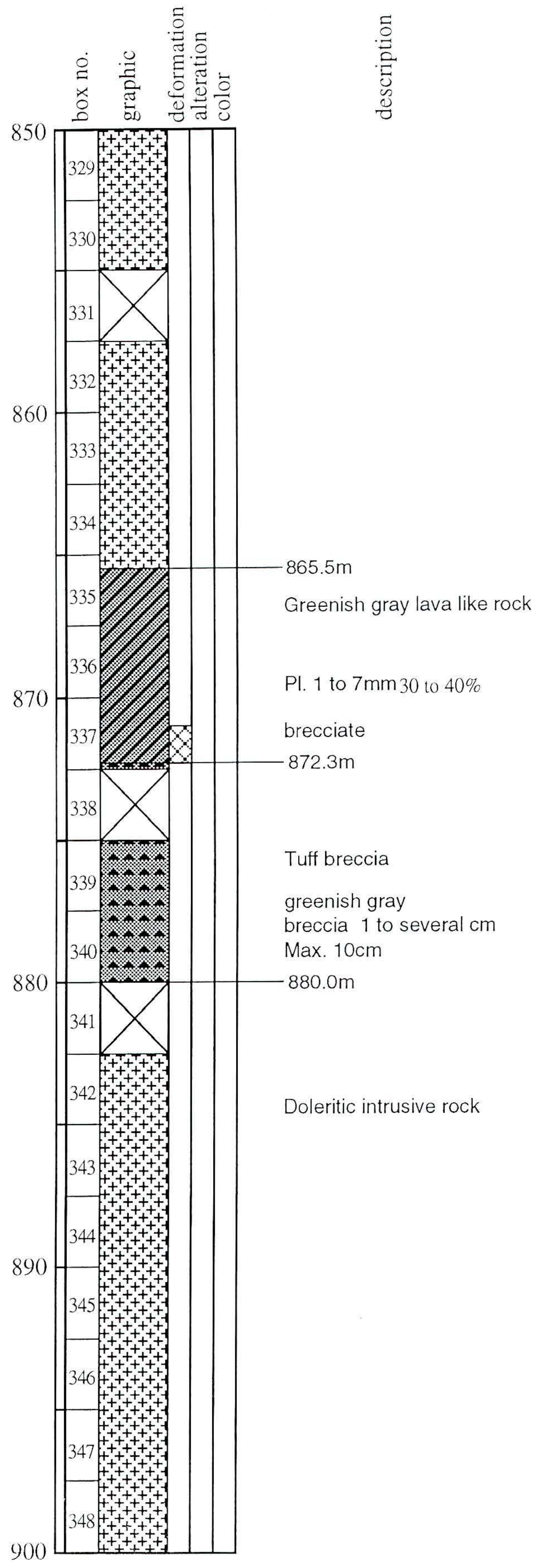


Drilling depth 700-800 m

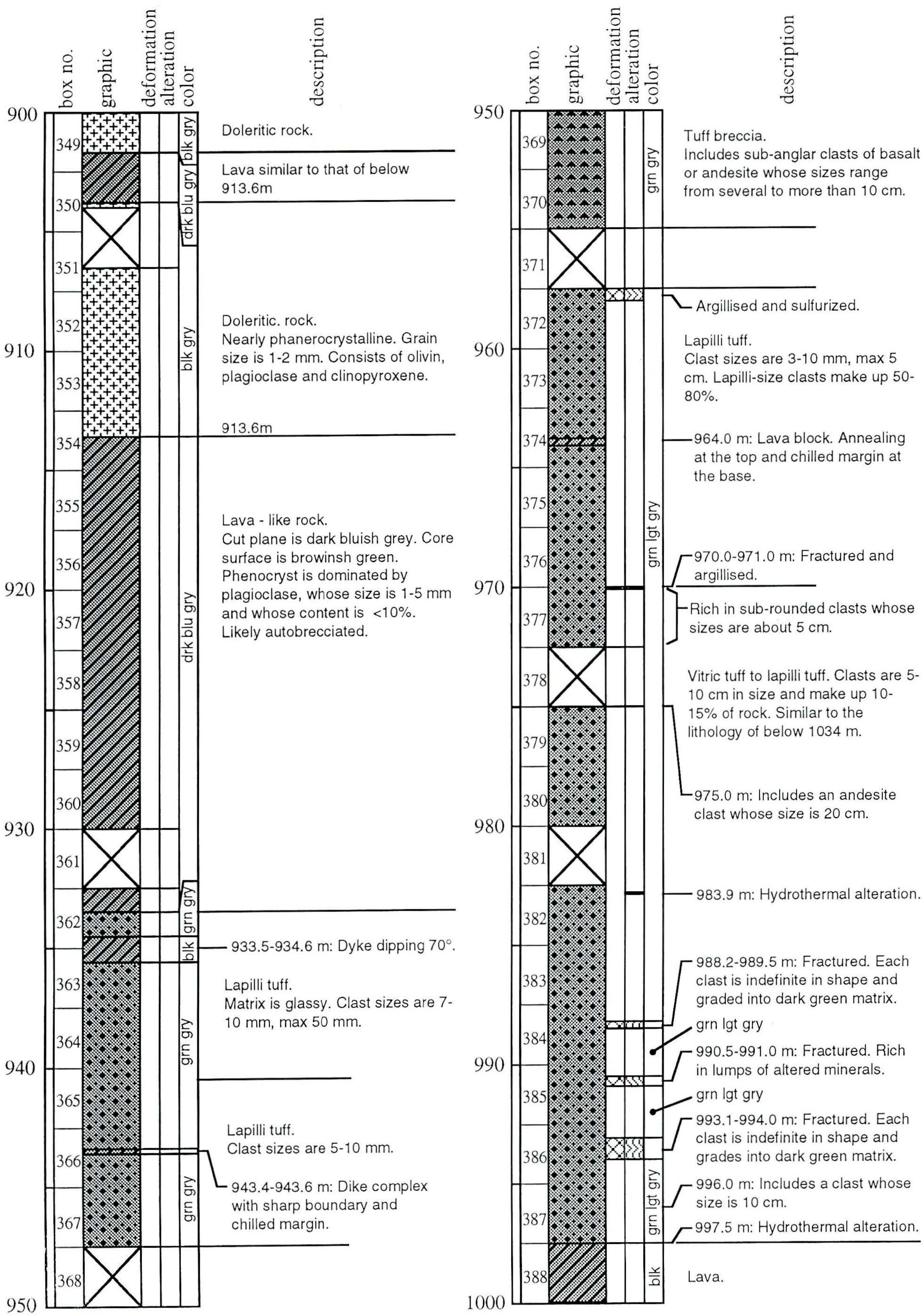


Drilling depth 800-900 m

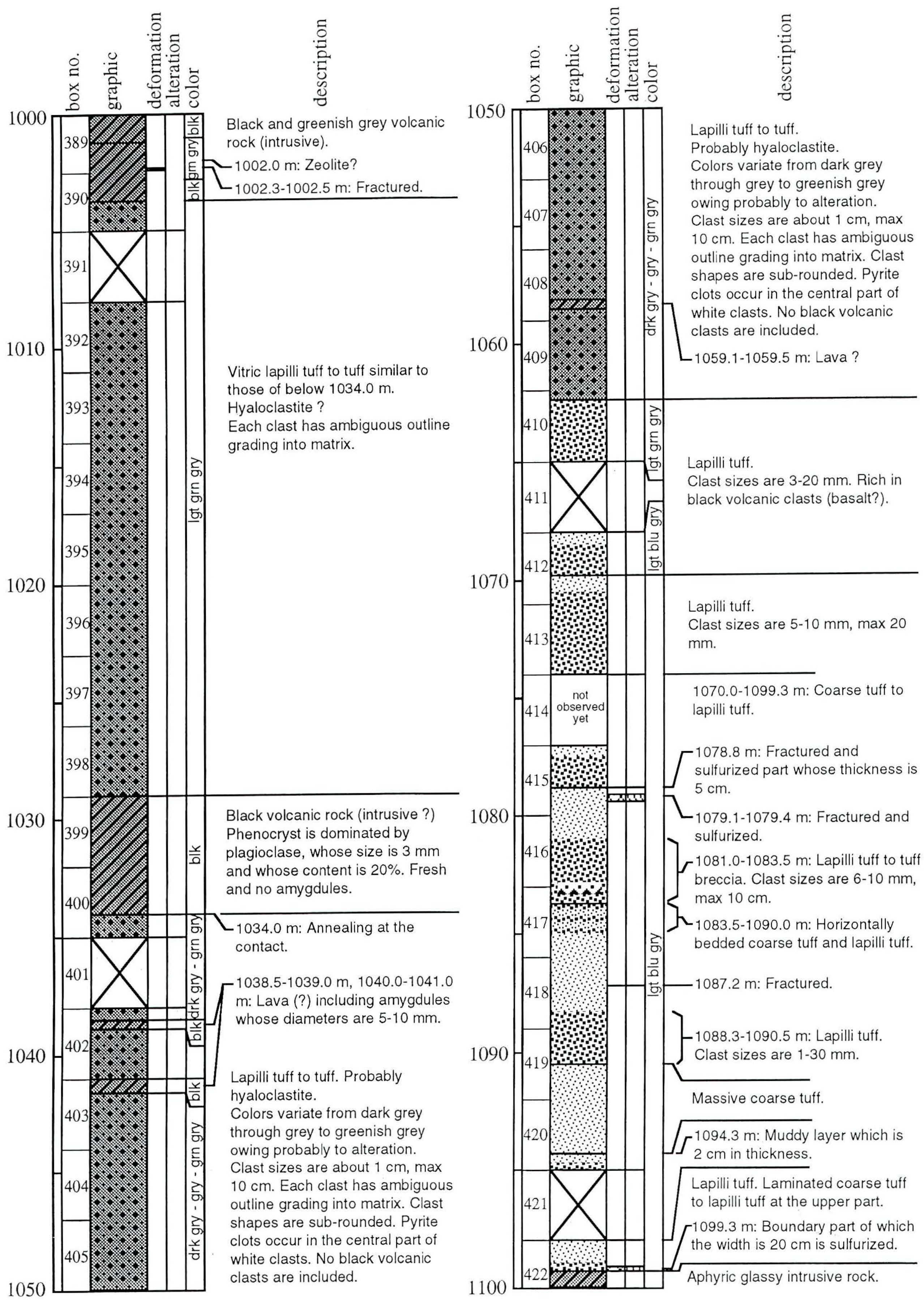




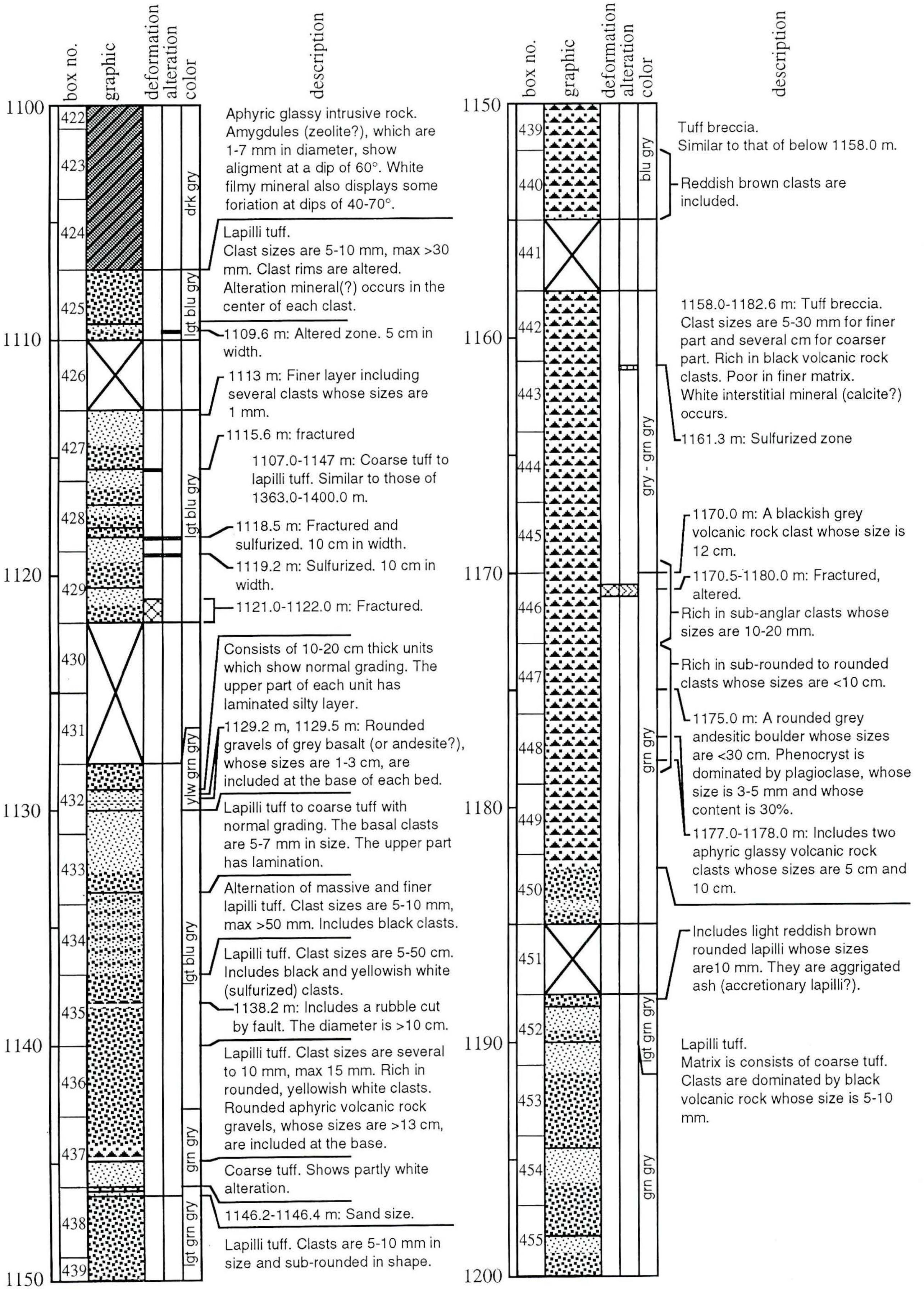
Drilling depth 900-1000 m



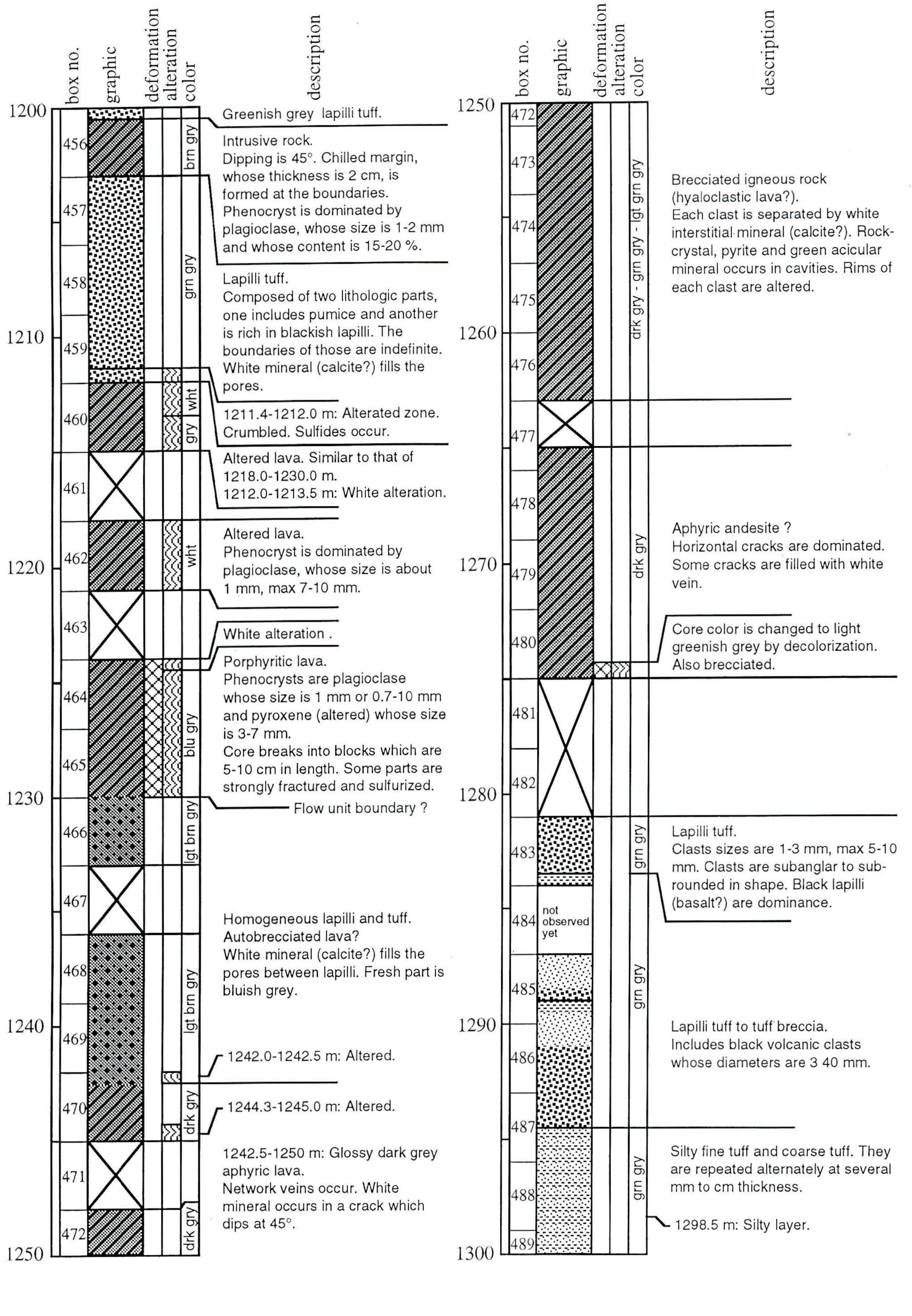
Drilling depth 1000-1100 m



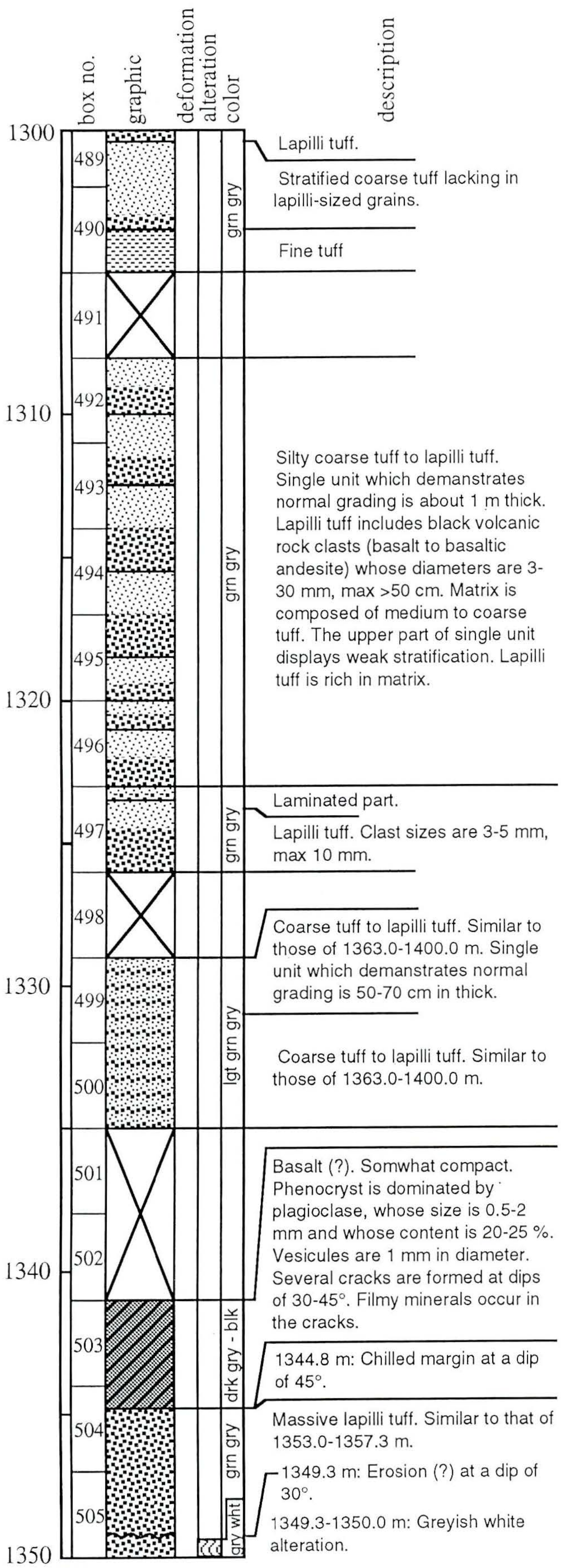
Drilling depth 1100-1200 m

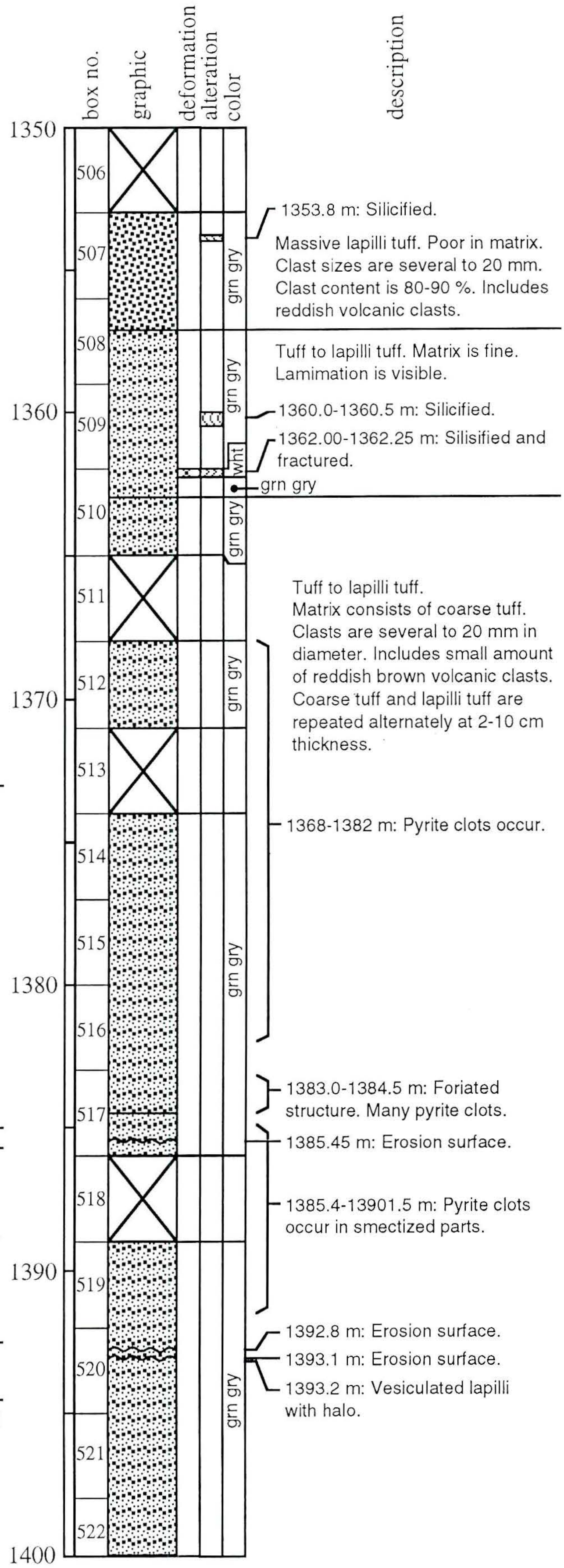


Drilling depth 1200-1300 m

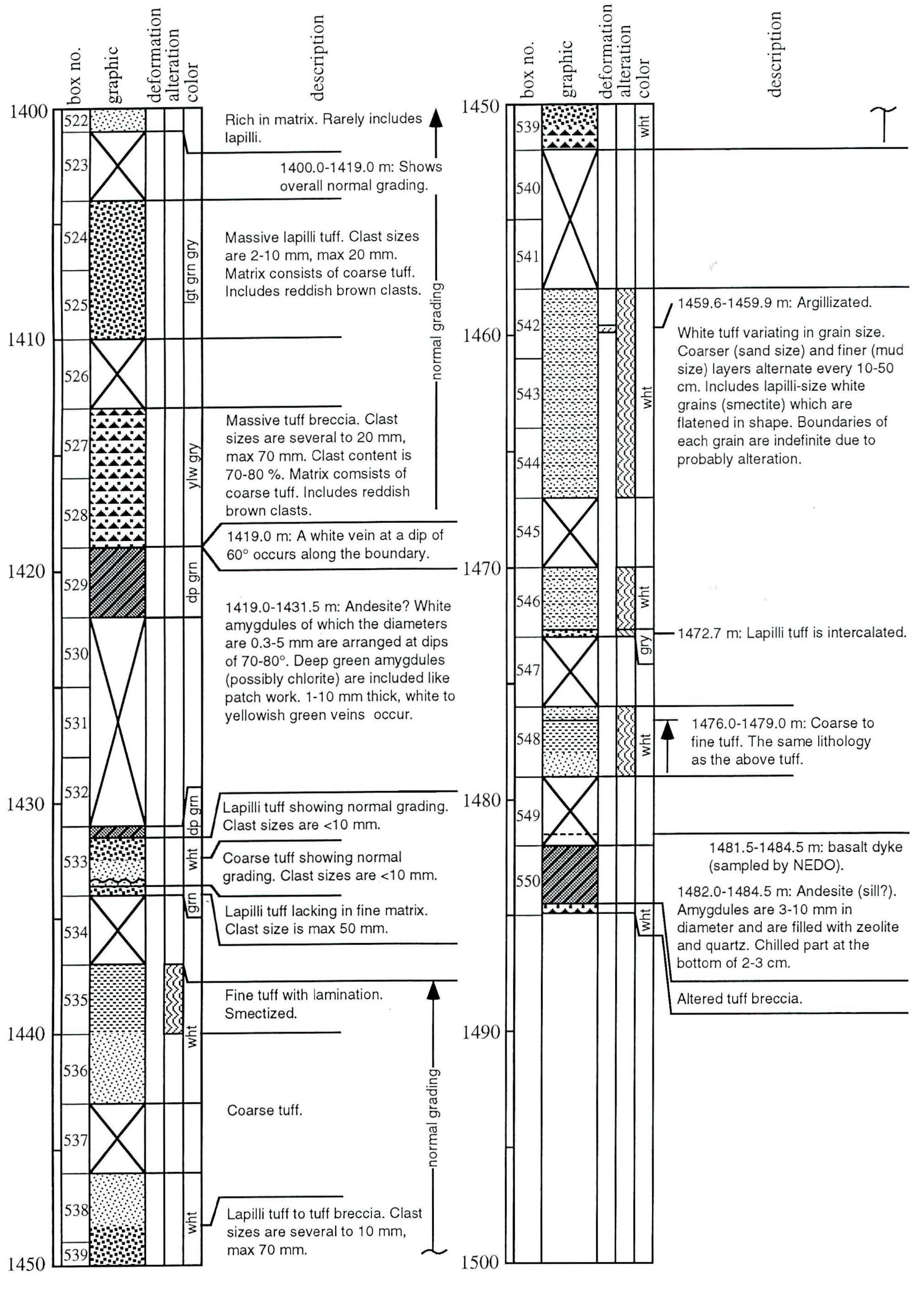


Drilling depth 1300-1400 m





Drilling depth 1400-1500 m



Appendix 2. Petrographic description of volcanic rocks.

Thin section no.: HJ4-01048 (Fig. 4-1).
Drilling depth: 104.8 meter.
Rock name: basaltic andesite.
Phenocryst: plagioclase, orthopyroxene and Fe-Ti oxide.

Plagioclase: euhedral to anhedral grain (0.2-4mm in diameter) occurring as glomeroporphyritic or discrete single grain. Three types of inner texture are noted in plagioclase phenocrysts; (type 1) crystal covered by honeycomb texture (Fig. 4-1), (type 2) crystal with dusty zone parallel to the crystal plane, and (type 3) clear crystal. Types 1 and 2 are dominant. Most of inclusions in plagioclase phenocryst are Fe-Ti oxide and orthopyroxene. Melt inclusions are locally replaced by Fe-Ti oxide and orthopyroxene.

Orthopyroxene: subhedral or glomeroporphyritic grain (0.5-1.5 mm in length) with clinopyroxene reaction rim. It shows close spatial association with Fe-Ti oxide.

Fe-Ti oxide: euhedral grain (0.07-0.2 mm in diameter) showing close spatial association with plagioclase and orthopyroxene.

Groundmass: intergranular texture, consisting of clinopyroxene (0.02-0.05 mm), plagioclase (0.05-0.15 mm), and Fe-Ti oxide (0.02-0.08 mm). High abundance of Fe-Ti oxide (Fig. 4-1) and subhedral to anhedral plagioclase are noted. Fe-Ti oxide shows rare abundance in areas around phenocryst. Patch of clinopyroxene is present (0.05 - 0.15 mm in diameter).

Thin section no.: HJ4-01075 (Fig. 4-2).
Drilling depth: 107. 5 meter.
Rock name: basaltic andesite.
Phenocryst: plagioclase, orthopyroxene, and Fe-Ti oxide.

Plagioclase: euhedral to anhedral grain (0.3-3.5 mm in diameter). Discrete plagioclase phenocrysts show higher abundance than glomeroporphyritic plagioclase grains. Addition to the three plagioclase types noted in the thin section no. HJ4-01048, another type of plagioclase with distinct inner textural (type4) is noted in this section. Type 4 plagioclase is characterized by a presence of core part covered by numerous small inclusions, surrounded by a inclusion rich zone paralleled to crystal plane. Most of plagioclase grains are smaller than 0.7 mm in diameter. Fe-Ti oxide and orthopyroxene are dominant inclusion. Melt inclusions are locally replaced by Fe-Ti oxide and orthopyroxene. Outer zone of some large plagioclase grains exhibits remarkable chemical zonal texture.

Orthopyroxene: subhedral grain (0.5-2.0 mm in length) with clinopyroxene reaction rim, showing close spatial association with Fe-Ti oxide.

Fe-Ti oxide: euhedral grain (0.1-0.5 mm in diameter).

Groundmass: intergranular texture, consisting of clinopyroxene (0.02-0.07 mm), plagioclase (0.05-0.15 mm), and Fe-Ti oxide (0.02-0.07 mm). High abundance of subhedral plagioclase (0.1-0.2 mm) is note. Clinopyroxene (0.07-0.15 mm) and Fe-Ti oxide (0.02-0.15 mm) are rare in areas surrounding phenocryst grains.

Thin section no.: HJ4-01493.
Drilling depth: 149.3 meter.
Rock name: basaltic andesite.

This rock consists of rock fragments and phenocrysts (0.2-4 mm in diameter) set in a glassy matrix. Dark-brownish fragments show a wide range of vesiculation texture and contain plagioclase unclusions (>0.7 mm). Light-brownish fragments contain trachytic plagioclase (>0.15 mm) and Fe-Ti oxide grains (>0.15 mm). Phenocrysts are plagioclase, orthopyroxene and clinopyroxene. Plagioclase is 0.5-1.5 mm in length. Some plagioclase grains exhibit type 1 honeycomb texture. Pyroxenes are 0.05-0.2 mm in diameter, and occur as glomeroporphyritic or single discrete grains.

Thin section no.: HJ4-02929 (Fig. 4-3).
Drilling depth: 292.9 meter.
Rock name: basalt.
Phenocryst: plagioclase and chloritized pyroxene.

Plagioclase: euhedral to subhedral grain (0.2-2 mm in diameter) occurring as glomeroporphyritic or single discrete grains. Addition to type 3 plagioclase, this rock contains other type plagioclase with distinct inner texture (type 5) characterized by a presence of inclusion rich zone parallel to crystal plane (Fig. 4-3). An outer most zone of type 5 plagioclase shows extensive chemical zoned texture.

Chlorite: alteration product after pyroxene, occurring as subhedral grain (0.2-0.3 mm in diameter) showing reaction rim of Fe-Ti oxide.

Groundmass: intergranular texture, consisting of plagioclase (0.05-0.3 mm), clinopyroxene (0.02-0.05 mm), and Fe-Ti oxide (0.02-0.07 mm).

Thin section no.: HJ4-03867 (Fig. 4-4).
Drilling depth: 386.7 meter.
Rock name: basaltic andesite.
Phenocryst: plagioclase and chloritized pyroxene.

Plagioclase: euhedral to subhedral grain (0.2-2.5 mm in diameter) occurring as glomeroporphyritic and single discrete grains. Types 1, 3 and 4 (Fig. 4-4) plagioclases are present.

Chlorite: alteration product after pyroxene, occurring as subhedral grain (1-2 mm in diameter).

Groundmass: hyalopilitic and glassy. plagioclase (0.02-0.2 mm), consisting of Fe-Ti oxide (<0.1 mm), chlorite (<0.02 mm) and brown glass.

Thin section no. : HJ4-05508 (Fig. 4-5).
Drilling depth : 550.8 meter.
Rock name : basalt.
Phenocryst : plagioclase and chloritized pyroxene

Plagioclase : euhedral to subhedral grain (0.3-3.7 mm in diameter) occurring as glomeroporphyritic and/or discrete grains. Types 3 (Fig. 4-5), 4 and 5 plagioclases are present. Type 4 is dominant.

Chlorite : subhedral grain (1-2 mm in diameter).

Groundmass : pilotaxitic consisting of plagioclase (0.05-0.2 mm), Fe-Ti oxide (0.02-0.05 mm), chlorite brown glass.

Thin section no. : HJ 4 -06225 (Fig. 4-6).
Drilling depth : 622.5 meter.
Rock name : basalt.
Phenocryst : plagioclase, orthopyroxene and clinopyroxene.

Plagioclase : euhedral grain (0.2-3 mm in diameter). Types 2, 3 and 4 are present. Some type 4 grains have core with small inclusions surrounded by a inclusion rich dusty zone. Most of the inclusions are Fe-Ti oxide or clinopyroxene. Melt inclusions are replaced by the above minerals. Most of the plagioclase phenocrysts smaller than 0.7 mm in diameter are clear crystal.

Orthopyroxene : subhedral grain (0.5-1.5 mm in diameter) occurring as glomeroporphyritic or single discrete grains with reaction rim of clinopyroxene and Fe-Ti oxide.

Clinopyroxene : rare abundance, subhedral grain. Some of phenocrysts include plagioclase (Fig. 4-6).

Groundmass : intergranular texture consisting of plagioclase (0.05-0.15 mm), clinopyroxene (0.02-0.07 mm) and Fe-Ti oxide (0.02-0.05 mm).

Thin section no. : HJ4-6258 (Fig. 4-7).
Drilling depth : 625.8 meter.
Rock name : basalt.
Phenocryst : plagioclase, orthopyroxene and clinopyroxene.

This rock is characterized by high abundances of phenocryst phases including plagioclase, orthopyroxene and clinopyroxene..

Plagioclase : euhedral grain (0.2-3 mm in diameter) occurring as clots. Types 1 (Fig. 4-7), 2, 3 and 4 plagioclases are present. Type 3 crystal is rare. Most of inclusions are Fe-Ti oxide and clinopyroxene. Melt inclusions are replaced by above minerals. Most of the phenocrysts smaller than 0.7 mm in diameter are clear crystal.

Orthopyroxene : subhedral grain (0.5-1.7 mm in diameter). Most of orthopyroxenes were replaced by chlorite.

Clinopyroxene : green colored, subhedral to subrounded crystal (0.5-4.0 mm in diameter). Low abundance.

Groundmass : Intergranular texture, consisting of plagioclase (0.05-0.2 mm), chlorite (0.02-0.07 mm) and Fe-Ti oxide (0.05-0.1 mm).

Groundmass shows extensive chloritization.

Thin section no. : HJ4-06532 (Fig. 4-8).
Drilling depth : 653.2 meter.
Rock name : basalt.
Phenocryst : plagioclase and clinopyroxene.

Plagioclase : euhedral grain (0.3-2.5 mm in diameter) occurring as both glomeroporphyritic (Fig. 4-8) or discrete grains. Types 3, 4 and 5 plagioclases are present. Most of them are type 3 .

Chlorite : alteration product after pyroxene, occurring as subhedral or anhedral grain (0.5-2.5 mm in diameter). Some of them are surrounded by reaction rim.

Groundmass : intersertal texture with high abundance of glass. It consists of plagioclase (0.05-0.2 mm), Fe-Ti oxide (0.02-0.07 mm), chlorite and altered glass.

Thin section no. : HJ4-06887 (Fig. 4-9).
Drilling depth : 688.7 meter.
Rock name : basalt.
Phenocryst : plagioclase and clinopyroxene. High abundance of phenocrysts (30 to 35 volume %) is noted.

Plagioclase : euhedral grain (0.2-3.0 mm in diameter). Most of plagioclases occur as glomeroporphyritic grains (Fig. 4-9). Types 3, 4 and 5 plagioclase are present. Type 3 is rare.

Clinopyroxene : euhedral grain (3.0 mm in diameter). This phase is weakly altered by chloritization.

Chlorite : alteration product after pyroxene. subhedral to anhedral grain (0.5-1.2 mm in diameter).

Groundmass : intersertal texture, showing high abundance of glass (partly altered) together with plagioclase (0.05-0.2 mm), Fe-Ti oxide (0.02-0.07 mm) and chlorite (0.05-0.15 mm).

Thin section. : HJ4-07349 (Fig. 4-10, -11).
Drilling depth : 734.9 meter.
Rock name : basalt.
Phenocryst : plagioclase , olivine , clinopyroxene , orthopyroxene and Fe-Ti oxide.

Plagioclase: euhedral, subhedral or unhedral crystal (0.2-4.5 mm in diameter). Glomeroporphyritic crystals are abundant with subordinate amounts of discrete phenocryst. Types 1, 2 and 3 plagioclases are present. Most of plagioclase are type 1 or type 2 (Fig. 4-10). Type 3 crystals and olivine occur as glomeroporphyritic grain. Most of types 1 and 2 crystals are 0.2-2.0 mm in diameter while those of type 3 are relatively large crystals (1.5-4.5 mm in diameter). Some of Type 3 crystals have reaction rim consisting of clinopyroxene and Fe-Ti oxide.

Olivine : subhedral to unhedral grain (1.5-4 mm in diameter). Most of olivine grains are extensively altered and replaced by iddingsite (Fig. 4-11).

Clinopyroxene : euhedral grain (0. 5-1 mm in diameter) occurring as discrete phenocryst.

Orthopyroxene : euhedral to subhedral grains (0. 3-1 mm in diameter), occurring as glomeroporphyritic grain and/or clots. Glomeroporphyritic grains have reaction rim of clinopyroxene and Fe-Ti oxide. Some of them show close spatial association with Fe-Ti oxide and/or plagioclase.

Fe-Ti oxide : euhedral grain (0. 5-2 mm in diameter).
Groundmass : intergranular texture consisting of plagioclase (0. 05-0. 15 mm), clinopyroxene (0. 02-0. 05 mm) and Fe-Ti oxide (0. 02-0. 05 mm).

Thin section no. : HJ4-07964 (Fig. 4-12).
Drilling depth : 796. 4 meter.
Rock name : basalt.
This sample is heterogeneous rock consisting of mafic and felsic parts (Fig. 4-12).
1). Mafic part
Phenocryst : plagioclase, olivine, clinopyroxene, orthopyroxene, chloritized pyroxene and Fe-Ti oxide.

Plagioclase : euhedral to subhedral crystal (0. 2- 2 mm in diameter). Glomeroporphyritic plagioclases are abundant with subordinate amounts of discrete plagioclase phenocryst. Types 1, 2, and 3 plagioclases are present. Most of plagioclase are type 1 or type 2. Type 3 crystals and olivine occur as glomeroporphyritic grain. Type 3 are relatively large crystals (5-7 mm in diameter).

Olivine : subhedral or unhedral grain (1. 2-2. 1 mm in diameter). All of olivine crystals are closely spatially associated with type 3 plagioclase. Most of olivines are extensively altered and replaced by iddingsite.

Clinopyroxene : euhedral grain (2-2. 5 mm in diameter).
Orthopyroxene : subhedral grains (0. 5-1 mm in diameter) with reaction rim.

Chlorite : subhedral to unhedral grain (0. 2-1 mm in diameter).
This phase is alteration product after pyroxene.

Fe-Ti oxide : euhedral grain (0. 2-0. 5 mm in diameter).
Groundmass : intergranular texture consisting of plagioclase (0. 15-0. 3mm), Fe-Ti oxide (0. 02-0. 05 mm), and brown glass.
2). Felsic part
Phenocryst : plagioclase and Fe-Ti oxide.

Plagioclase : euhedral to subhedral crystal (0. 3-3 mm in diameter). Glomeroporphyritic crystals are abundant with subordinate amounts of discrete phenocryst. Types 3 and 5 plagioclases are present.

Fe-Ti oxide : euhedral grain with 0. 1-0. 3 mm in diameter.
Groundmass : intersertal texture consisting of plagioclase (0. 05-0. 2 mm), Fe-Ti oxide (0. 1 mm) and brown glass.

Thin section no. : HJ4-08015 (Fig. 4-13).
Drilling depth : 801. 5 meter
Rock name : basalt.
Phenocryst : plagioclase and clinopyroxene.

Types 2, 3 and 5 plagioclases are present. Most of plagioclases are type 5 (Fig. 4-13). Some of the crystals (0. 3-0. 5 mm in diameter) occur as clots with clinopyroxene (0. 1-0. 3 mm in diameter)

Clinopyroxene : subhedral to unhedral grain (0. 3-1. 5 mm in diameter). Some crystals have a reaction rim.

Groundmass : hyalopillitic texture consisting of plagioclase (0. 05-0. 2 mm), Fe-Ti oxide (0. 1 mm) and brown glass.

Thin section no. HJ4-08906 (Fig. 4-14).
Drilling depth : 890. 6 meter.
Rock name : dolerite.
Phenocryst : plagioclase, clinopyroxene, orthopyroxene and Fe-Ti oxide.

Plagioclase : subhedral to unhedral crystal (0. 2-2. 2 mm in diameter). Most of the plagioclases are clear crystals.

Clinopyroxene : euhedral or subhedral grain (0. 8-1. 5 mm in diameter).

Orthopyroxene : euhedral, subhedral, or unhedral grain (2-3. 7 mm in diameter).

Fe-Ti oxide : euhedral or subhedral grain (0. 4-0. 6 mm in diameter).

Thin section no. : HJ4-09351 (Fig. 4-15).
Drilling depth : 935. 1 meter.
Rock name : basalt.
Phenocryst : plagioclase and orthopyroxene.

Plagioclase : euhedral to subhedral crystal (0. 2-2 mm in diameter). Glomeroporphyritic crystals are abundant with subordinate amounts of discrete phenocryst. Most of the crystals are less than 1 mm in diameter. Types 3, 4 and 5 (Fig. 4-15) plagioclases are present. Most of plagioclase are type 4 or type 5.

Orthopyroxene : subhedral grain (2 mm in diameter) locally including plagioclase.
Groundmass : intersertal texture consisting of plagioclase (0. 05-0. 1 mm), Fe-Ti oxide (0. 02-0. 07 mm) and brown glass.

Thin section no. : HJ4-10315 (Fig. 4-16).
Drilling depth : 1031. 5 meter.
Rock name : basalt.
Phenocryst : plagioclase and Fe-Ti oxide.

Plagioclase : euhedral to subhedral crystal (0. 5-2 mm in diameter). Glomeroporphyritic crystals are abundant with subordinate amounts of discrete phenocryst. Types 3, 4 and 5 (Fig. 4-16) plagioclases are present. Most of the crystals are type 4 or type 5.

Fe-Ti oxide : euhedral grain (0. 3-0. 5 mm in diameter).

Groundmass : intersertal texture consisting of plagioclase (0.05-0.1 mm), Fe-Ti oxide (0.02-0.07 mm) and brown glass.

Thin section no. : HJ4-11004 (Fig. 4-17).
Drilling depth : 1100.4 meter.
Rock name : basalt.
Phenocryst : plagioclase and chloritized pyroxene.

Plagioclase : euhedral to subhedral crystal (0.2-3 mm in diameter). Most of the crystals are less than 1 mm in diameter. Glomeroporphyritic crystals are abundant with subordinate amounts of discrete phenocryst. Types 3, 4 and 5 plagioclases are present. Most of the crystals are type 4. Type 3 crystals occur as relatively large grains (> 2 mm in diameter) (Fig. 4-17).

Chlorite : alteration product after pyroxenes, occurring as subhedral or unhedral grain (1-2 mm in diameter).

Groundmass : hyalopillitic texture consisting of plagioclase (0.05-0.1 mm), Fe-Ti oxide (0.3-0.5 mm) and brown glass.

Thin section no. : HJ4-12290 (Fig. 4-18).
Drilling depth : 1229.0 meter.
Rock name : basaltic andesite.
Phenocryst : plagioclase, chloritized pyroxene, and Fe-Ti oxide.

Plagioclase : euhedral to subhedral crystal (0.5-1.3 mm in diameter). Glomeroporphyritic crystals are abundant with subordinate amounts of discrete phenocryst. Type 3 and 4 plagioclases are present. Most of the crystals are type 3 (Fig. 4-18).

Clinopyroxene : subhedral to unhedral grain (0.2-0.5 mm in diameter) partly chloritized. Most of the crystals are closely spatially associated with plagioclase.

Fe-Ti oxide : euhedral to subhedral grain (0.1-0.25 mm in diameter).

Groundmass : hyalopillitic texture consisting of plagioclase (0.02-0.1 mm), Fe-Ti oxide (0.02-0.05 mm) and brown glass.

Thin section no. : HJ4-12733 (Fig. 4-19).
Drilling depth : 1273.3 meter.
Rock name : aphyric andesite.
Phenocryst : poor.
Groundmass : pilotaxitic texture consisting of plagioclase (0.05-0.2 mm) (Fig. 4-19), Fe-Ti oxide (0.02-0.05 mm) and brown glass.

Thin section no. : HJ4-13426 (Fig. 4-20).
Drilling depth : 1342.6 meter.
Rock name : basalt.
Phenocryst : plagioclase and chloritized pyroxene.

Plagioclase : euhedral to subhedral grain (0.2-2.5 mm in diameter) occurring as glomeroporphyritic and/or discrete grains. Types 3 (Fig. 4-20), 4 and 5 plagioclases are present. Most of the crystals are type 4 and type 5.

Chlorite : alteration product after pyroxenes, occurring as subhedral to unhedral grain (0.3-1.2 mm in diameter). Most of chlorite grains (after pyroxenes) are closely spatially associated with plagioclase.

Groundmass : hyalopillitic texture consisting of plagioclase (0.05-0.2 mm), Fe-Ti oxide (0.02-0.05 mm) and brown glass.

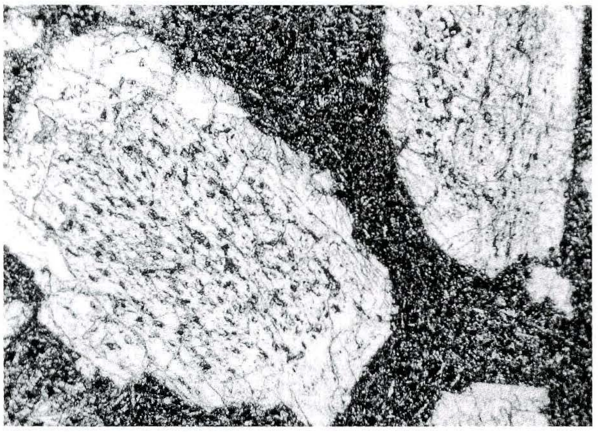
Thin section no. : HJ4-14215 (Fig. 4-21).
Drilling depth : 1421.5 meter.
Rock name : basalt
Phenocryst : plagioclase, chloritized pyroxene and Fe-Ti oxide.

Plagioclase : euhedral, to subhedral crystal (0.3-3 mm in diameter). Types 2, 3, 4 and 5 plagioclases are present. Most of grains are type 3 (Fig. 4-21) or type 4.

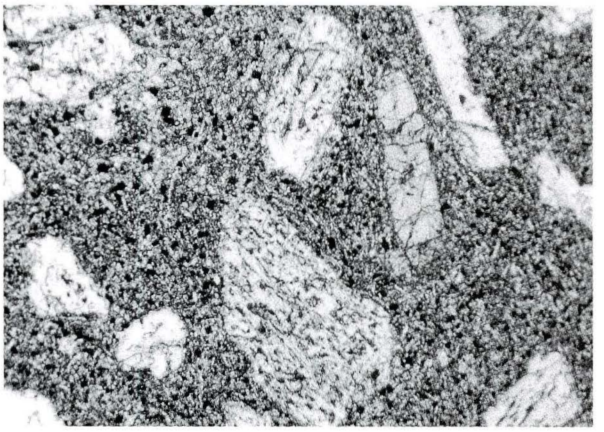
Chlorite : alteration products after pyroxenes. It occurs as subhedral or unhedral grain (0.2-1.5 mm in diameter) and totally replaced pyroxene grains. Most of chlorite grains are closely associated with plagioclase.

Groundmass : hyalopillitic texture consisting of plagioclase (0.05-0.2 mm), Fe-Ti oxide (0.02-0.1 mm) and brown glass.

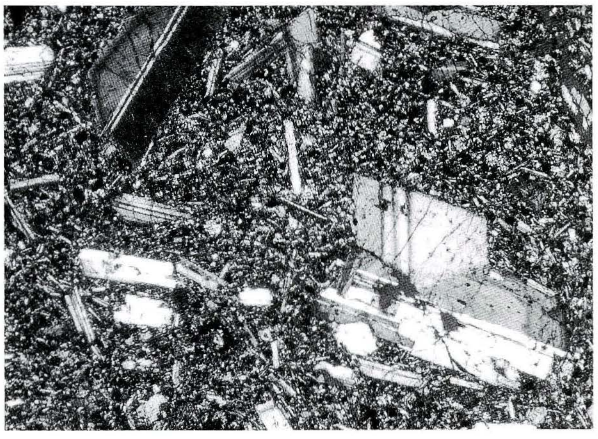
Fig. 4. Microphotographs of volcanic rock of the core sample. Width of field of view is 3. 5 mm. See Appendix 2 for detailed description.



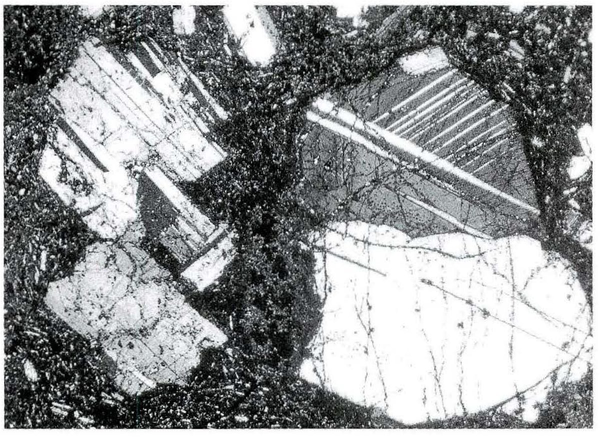
4-1. Thin section no. : HJ4-01048, opened nicols.



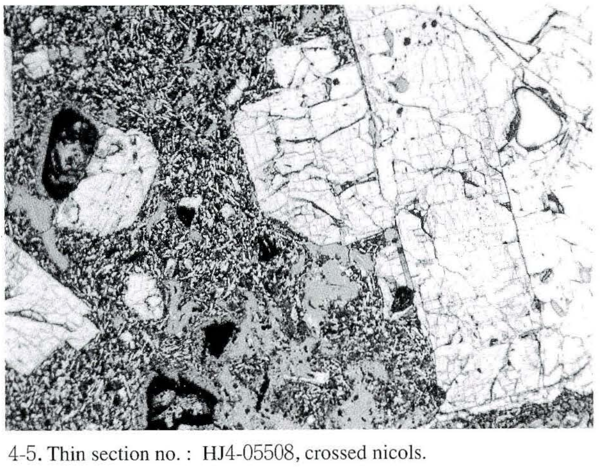
4-2. Thin section no. : HJ4-01075, opened nicols.



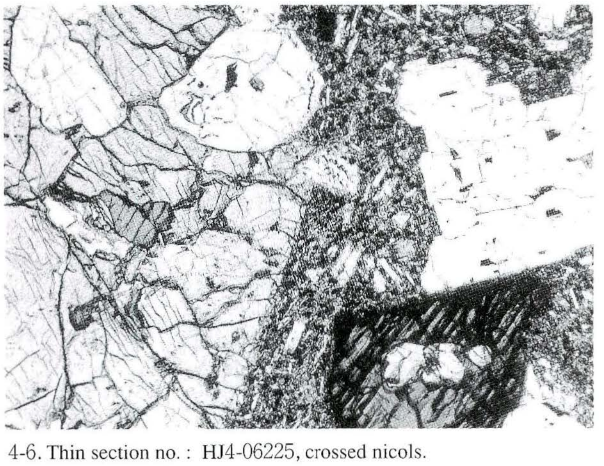
4-3. Thin section no. : HJ4-02929, crossed nicols.



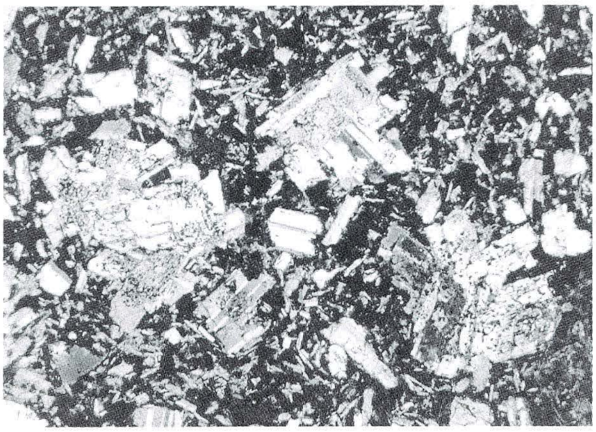
4-4. Thin section no. : HJ4-03867, crossed nicols.



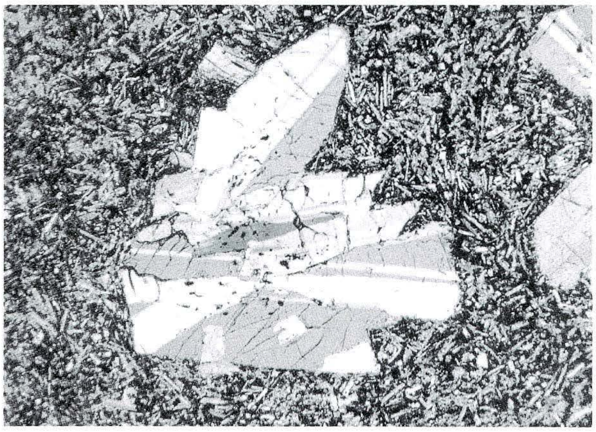
4-5. Thin section no. : HJ4-05508, crossed nicols.



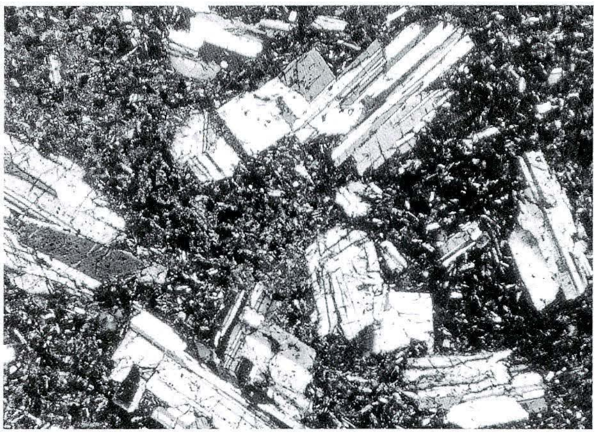
4-6. Thin section no. : HJ4-06225, crossed nicols.



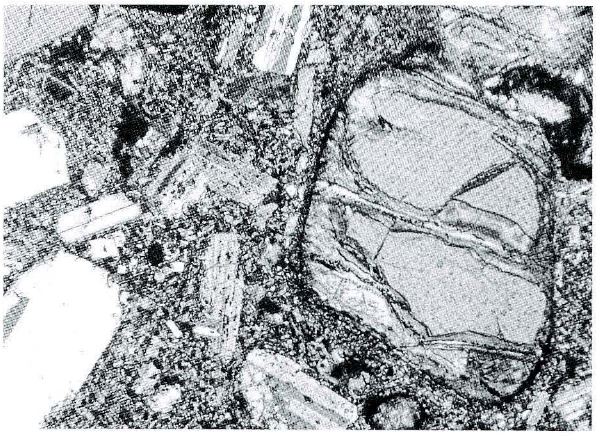
4-7. Thin section no. : HJ4-06258, crossed nicols.



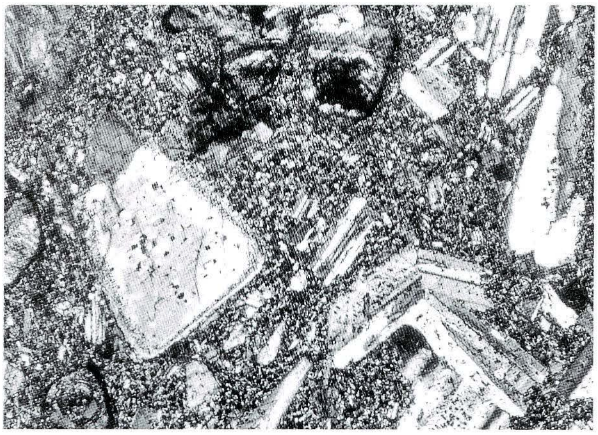
4-8. Thin section no. : HJ4-06532, crossed nicols.



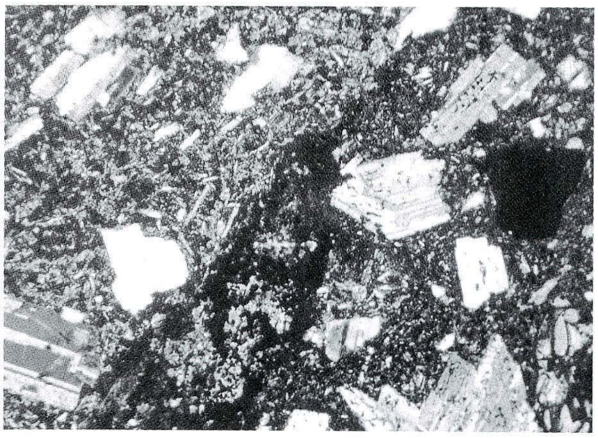
4-9. Thin section no. : HJ4-06887, crossed nicols.



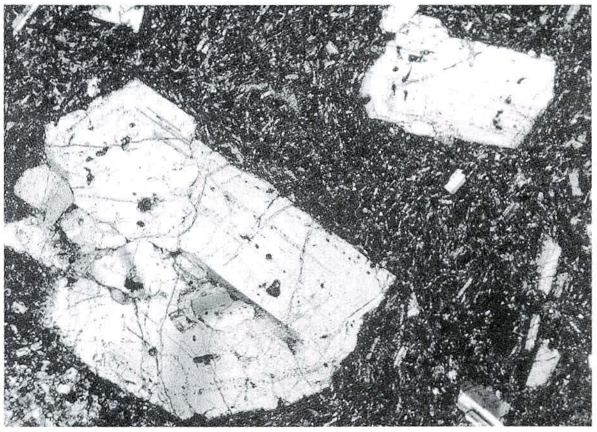
4-10. Thin section no. : HJ4-07349, crossed nicols.



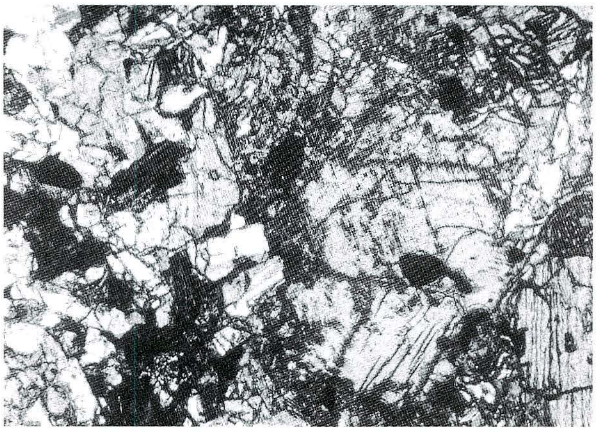
4-11. Thin section no. : HJ4-07349, crossed nicols.



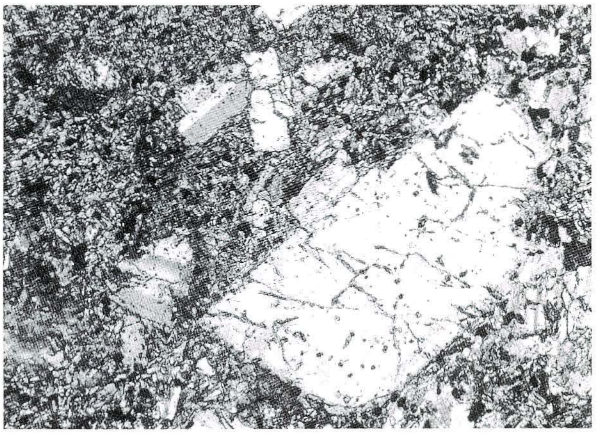
4-12. Thin section no. : HJ4-07964, crossed nicols.



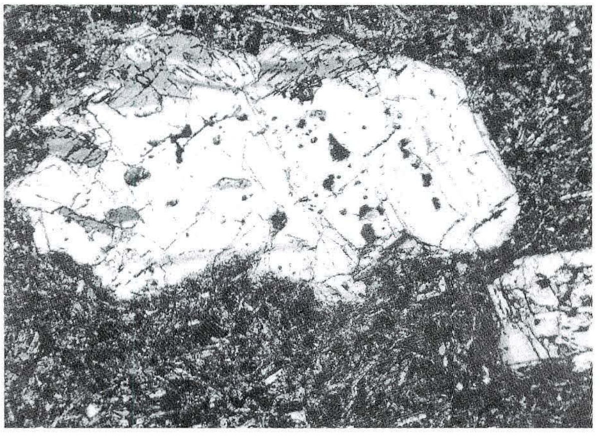
4-13. Thin section no. : HJ4-08015, crossed nicols.



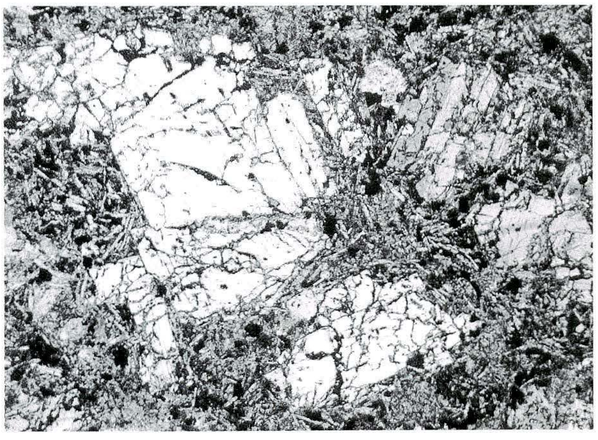
4-14. Thin section no. : HJ4-08906, crossed nicols.



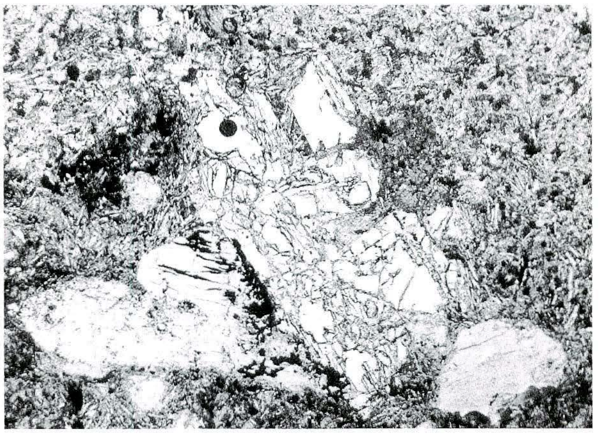
4-15. Thin section no. : HJ4-09351, crossed nicols.



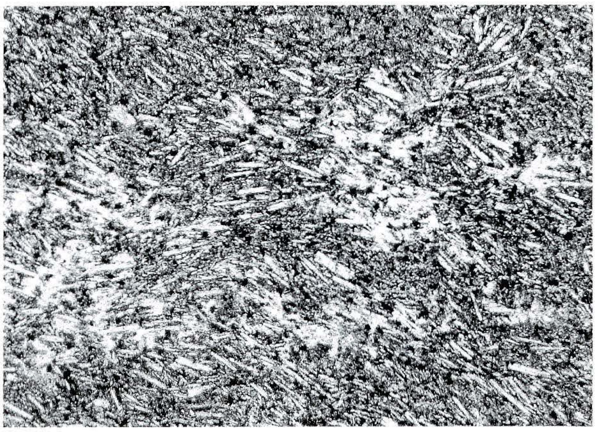
4-16. Thin section no. : HJ4-10315, crossed nicols.



4-17. Thin section no. : HJ4-11004, crossed nicols.

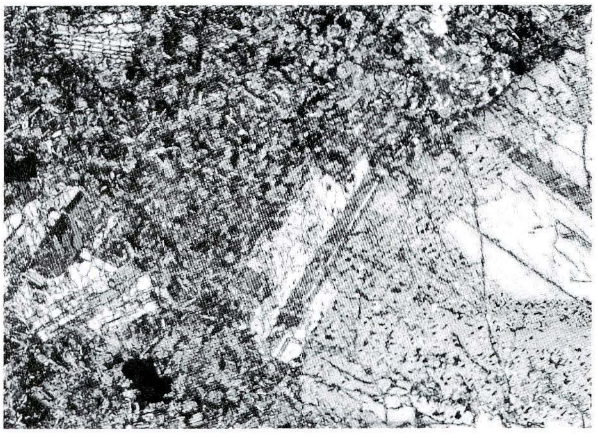


4-18. Thin section no. : HJ4-12290, opened nicols.



4-19. Thin section no. : HJ4-12733, opened nicols. eek

4-20. Thin section no. : HJ4-13426, crossed nicols.



4-21. Thin section no. : HJ 4 -14215, crossed nicols.