



Foto 13 Firma de la lista de equipos donados entre el Embajador Plenipotenciario en Bolivia Sr. Yoshimizu y el Lic. P. Ramos Rector de la UMSA.



Foto 14 Vista de la recepción ofrecida por la UMSA despues de la ceremonia de entrega de equipos (Julio de 1983 en IGE). Izquierda Lic. P. Ramos Rector de la UMSA, Lic. L. Soruco miembro del CEUB, Lic. R. Rada presidente del CEUB, Dr. R. Costas Vice Rector de la UMSA, Ing. E. Vargas UMSA, Dr. F. Cordero secretario General de la UMSA.



Foto-15 Igual anterior. Izquierda Sr. Yoshimizu Embajador Plenipotenciario en Bolivia, Ing. O. Sanjines Ex Director del IGE, M. Ann secretaria, Lic. J. Omoya miembro de la Embajada del Japon, Sr. Masahiko Kobayashi Tercer secretario de la Emabajada del Japon.



Foto-16 Presentación y explicación de los equipos donados al relacionador de la Universidad en julio de 1983.

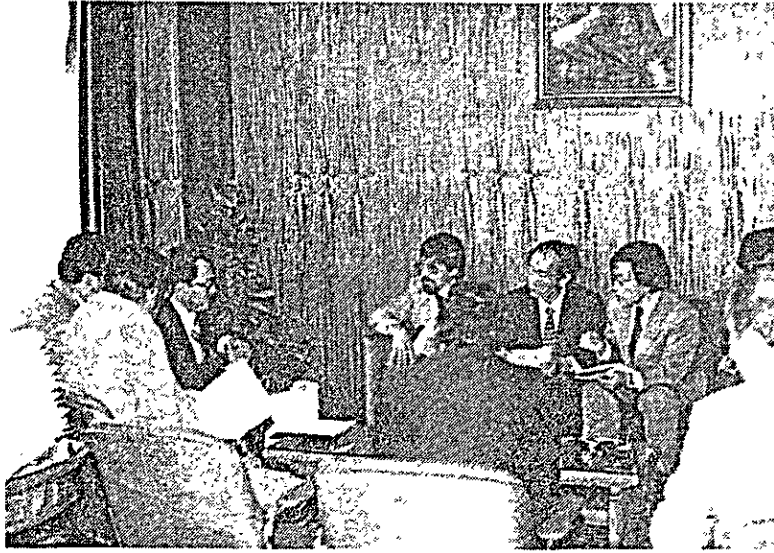


Foto-17 4to Comite Mixto (Septiembre 15 de 1983 en el Rectorado de la UMSA). Aprobación de los planos de distribución de ambientes y asignación de nuevos investigadores para la contraparte. Lic. P. Ramos Rector de la UMSA (izquierda), Lic. J. Omoya miembro de la Embajada del Japon, Dr. Shinpei Kano Jefe asesor, Sr. Toshio Asano de JICA en La Paz.

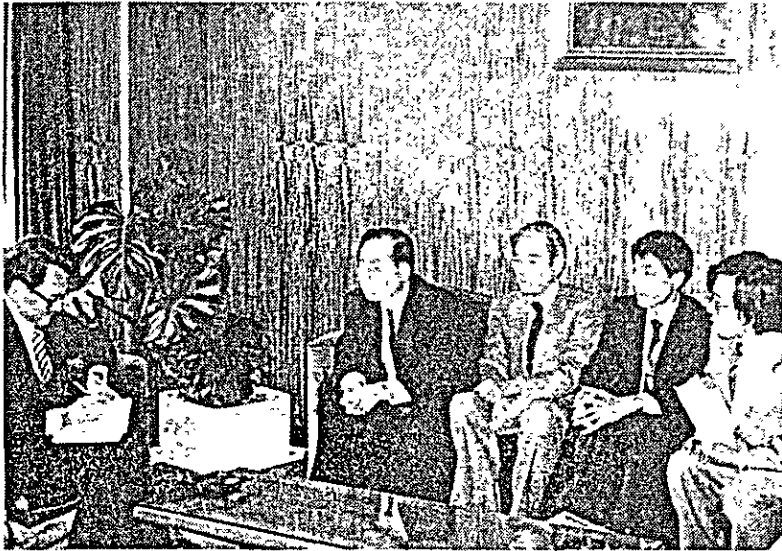


Foto-18 5to Comite Mixto (Octubre 4 de 1983). Reunion sobre los objetivos de la Mision japonesa.-informe preliminar del proyecto del Instituto de Geología Económica (Prof. Asahiko Sugaki Jefe de la Mision y otros tres miembros), Izquierda Lic. P. Ramos Rector de la UMSA, Prof. A. Sugaki de la Universidad de Tohoku, Sr. Minoru Ishi miembro del Ministerio de Educación del Japon, Prof. Ad. Hiroto Ueno de la Universidad de Tohoku, Sr. Toshio Asano de la oficina de JICA en La Paz.



Foto-19 6to Comite Mixto (Octubre 11 de 1983 en el Rectorado de la UMSA). Información de investigación y resumen del estudio y conferencias. Izquierda Lic. P. Ramos Rector de la UMSA, Prof. Asahiko Sugaki de la Universidad de Tohoku, Lic. Minoru Ishii del Ministerio de Educación del Japon, Prof. Ad. Hirotomo Ueno de la Universidad de Tohoku, Lic. J. Omoya miembro de la Embajada del Japon.



Foto-20 Firma del acta entre el Lic. P. Ramos Rector de la UMSA y el Prof. A. Sugaki de la Universidad de Tohoku en el 6to Comite Mixto.

### 3.2 Informe de orientación técnica

#### 3.2.1 Introducción

Trabajo de expertos foto-1. La primera época fue utilizada para determinar la ubicación exacta de los equipos donados e instalación de los servicios eléctricos agua potable y alcantarillado, no hubo una orientación técnica sistemática. La segunda parte del tiempo se utilizó para dictar cursos de capacitación y orientación en el manejo de equipos que llegaron al IGE. La parte final del tiempo fue de instalación de los equipos donados y ajuste de los mismos, conferencia para explicar el manejo de equipos, y prácticas de laboratorio para aprender el uso de los mismos.

|                            | 1982 |                      | 1983                 |          |          |  |   |                    |   |                    |   |                    |                     |             |
|----------------------------|------|----------------------|----------------------|----------|----------|--|---|--------------------|---|--------------------|---|--------------------|---------------------|-------------|
|                            | 11   | 12                   | 1                    | 2        | 3        | 4  | 5 | 6                  | 7 | 8                  | 9 | 10                 |                     |             |
| Steering Committee         |      | 1 ●                  |                      | ●2       |          |  |   | ●3                 |   |                    |   | 4 ●                | 5 ●                 | 6 ●         |
| Business                   |      | Lecture by Sugaki    |                      |          |          | Lecture by Kano, Nambu, Mizota, Nakada & Hayashi |   |                    |   | Setting equipments |   |                    | Practice Chem analy |             |
| Field or mine Survey       |      | La Paz, Potosi Uyuni |                      |          | San Jose |  |   | Huayna P. San Jose |   | Potosi             |   | Sajama             | Taqesi              | Indipend    |
| Equipment Arrival (La Paz) |      |                      | ○ Kano Mizota Nakada | ○ Ford B |          | ○ Hayashi  |   | ○ Type w. Copy m.  |   | ○ Main equipments  |   | ○ Vacuum exhaust   |                     |             |
| Expert Stay                |      | Sugaki               |                      |          |          | Kano Mizota & Nakada                             |   |                    |   | Hayashi            |   | Yamamoto & Higashi |                     | JICA misson |

Grafico - 1 Programa diario del proyecto del Instituto de Geología económica (Noviembre de 1982 - Octubre de 1983).

Inicialmente los cursos de capacitación fueron programados para enero de 1983, pero recién se pudo empezar a fines de marzo por las razones siguientes: atraso en la construcción del edificio del Instituto en el campus de Cota Cota, traslado del Instituto.

Apesar del tiempo perdido todos los expertos pudieron cumplir con su programa antes de fines de junio. Por otro lado se programó 3 meses para la instalación de los equipos donados; con este fin todos los expertos y miembros de la otra parte trabajaron con esfuerzo y celeridad de tal manera que se terminó de instalar en menos de un mes.

El resto del período se asignó para practicar con los equipos donados.

Los cursos de capacitación más importantes abarcaron los siguientes temas: conocimiento y manejo de equipos de investigación y conocimientos básicos sobre geología económica, mineralogía y petrología.

En diciembre de 1982 se realizaron dos conferencias especiales por el experto a corto tiempo Prof. Asahiko Sugaki de la Universidad de Tohoku sobre los temas "The Kuroko deposits in Japan" y "Synthesis of sulfide minerals and their phase equilibrium".

Antes de la llegada de los equipos donados el año 1982, se realizaron prácticas sobre utilización de los equipos traídos por los expertos antes de iniciar oficialmente este proyecto.

Las prácticas fueron las siguientes: microscopía petrográfica, microscopía de opacos, difracción de rayos-X, prácticas de análisis térmico diferencial, prácticas de inclusiones fluidas y prácticas con el equipo de fluorescencia de rayos-X.

La actividad de investigación y visitas a yacimientos se llevaron a cabo desde fines de noviembre de 1982 hasta mediados de diciembre, en minas de los departamentos de La Paz, Potosí y el Salar de Uyuni.

En el primer periodo desde marzo de 1983 se realizó una investigación en la mina San José de la ciudad de Oruro, con todos los expertos y contrapartes.

En la segunda parte, estos es, desde el mes de junio, se realizó una investigación adicional.

Desde julio hasta mediados de agosto de 1983 se llevo a cabo la investigación del distrito minero de Potosí en forma conjunta con la Misión de Ciencias del Ministerio de Educación del Japon (Jefe de la misión Prof. Hiroto Ueno de la Universidad de Tohoku). También en septiembre del mismo año se realizó la investigación de rocas erúptivas en dos áreas.

Los análisis de laboratorio se llevaron a cabo en forma conjunta por expertos japoneses y contra parte boliviana; sobre inclusiones fluidas de la mina San José, la petrografía y petrología del granito del Taquesí; además se investigó en forma conjunta utilizando varios equipos sobre muestras de rocas y minerales coleccionadas en el campo.

La actividad de investigación de la mina San Jose fue realizada en forma conjunta entre expertos y contrapartes; especialmente se estudió en vetas de la sección Itos, se hizo la investigación mineralógica del yacimiento, micro tectónica del yacimiento, petrografía y petrología, inclusiones fluidas y alteraciones en la misma zona.

Esta investigación retrazo en mayor tiempo la instalación y ajuste de los equipos donados y las prácticas correspondientes, por esta razón el resultado no es satisfactorio. Se continuó el siguiente año con las investigaciones de inclusiones fluidas, mineralogía, microtectónica con buen resultado. Especialmente la investigación química de las rocas erúptivas de la mina San José.

Durante un mes se repitió las prácticas de análisis químico por vía húmeda orientadas por el experto Mizota, siendo

de buen resultado el primer año del proyecto del Instituto de Geología económica. El informe de los resultados de estas investigaciones de la mina San José fue insertado en el capítulo 2 de este informe.



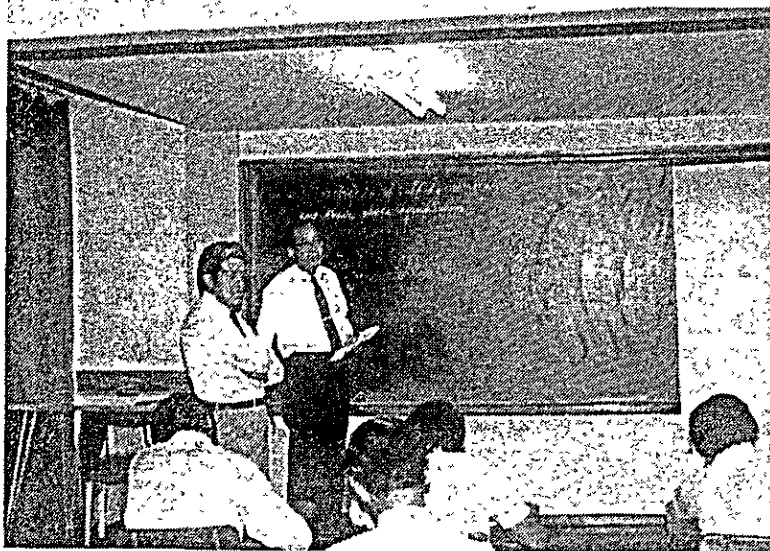


Foto-1 Experto A. Sugaki (corto tiempo) disertó sobre "Synthesis of sulfide and their phase equilibrium" (Diciembre 16 de 1982). El Ing. O. Sanjines Jefe del Instituto de Geología económica hizo de interprete.

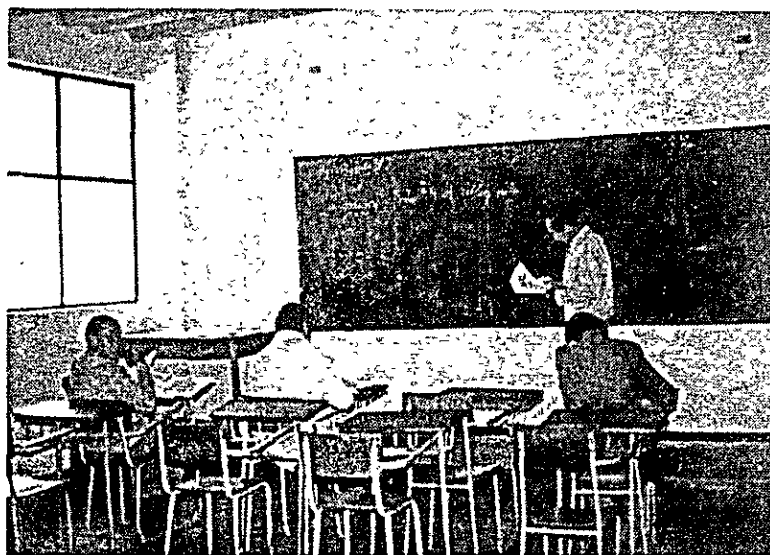


Foto-2 Jefe asesor Shinpei Kano dando clases de termodinámica, (Mayo 13 de 1983).

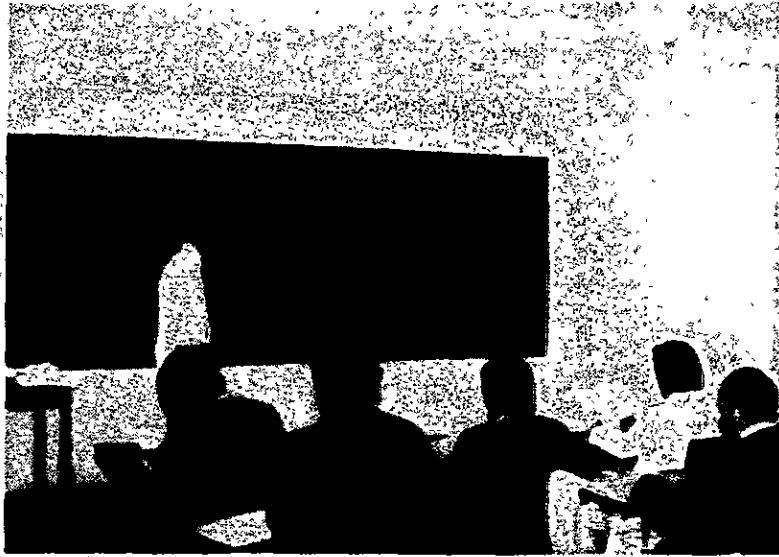


Foto-3 Experto Tadato Mizota dando clases sobre análisis de rayos-X (Marzo 16 de 1983).



Foto-4 Experto Kenichiro Hayashi dando clases de microscopía de opacos.

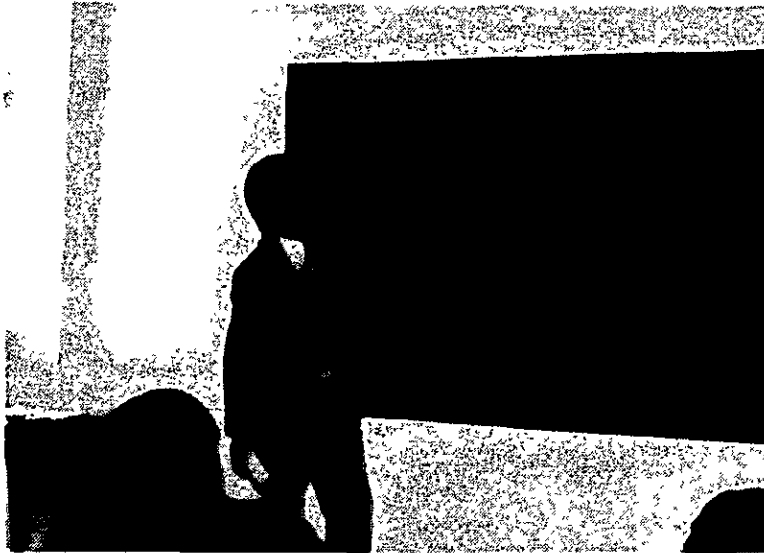


Foto-5 Experto Setsuya Nakada dando clases de petrología  
(Mayo 16 de 1983).

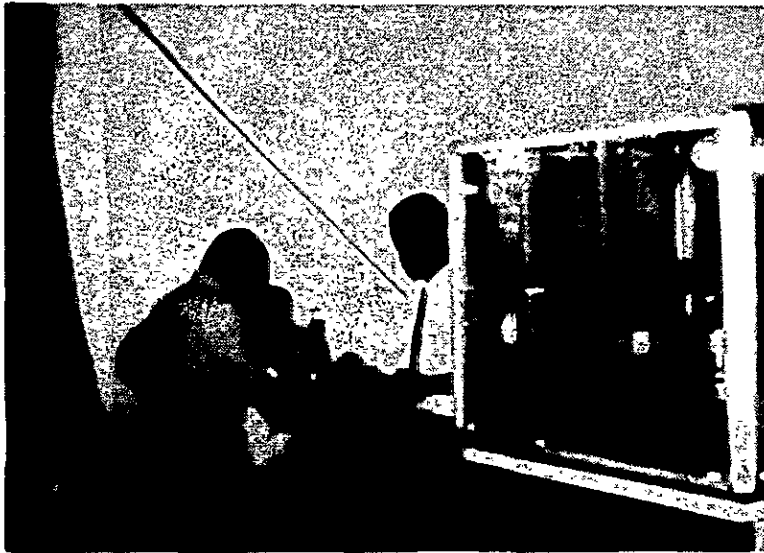


Foto-6 Experto Masateru Nambu encargado de las prácticas de  
inclusiones fluidas juntamente con el Lic. H. Villena  
y Sr. G. Sandi.

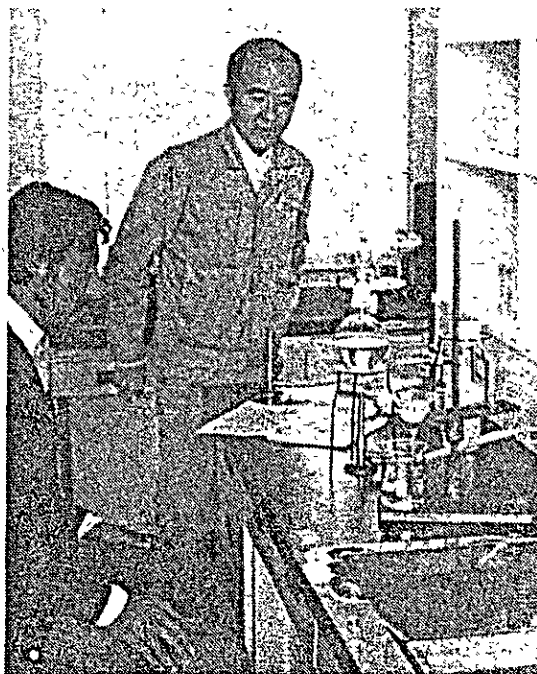


Foto-7 Experto T. Mizota encargado de las prácticas de análisis químico por vía húmeda y Sr. F. Saavedra.



Foto-8 Igual anterior, izquierda a derecha Ing. E. Soria, Lic. Villena, experto Mizota e Ing. Sanjines.



Foto-9 Experto Setsuya Nakada encargado de las prácticas de microscopía, Sr. F. Saavedra y Sr. Castillo.

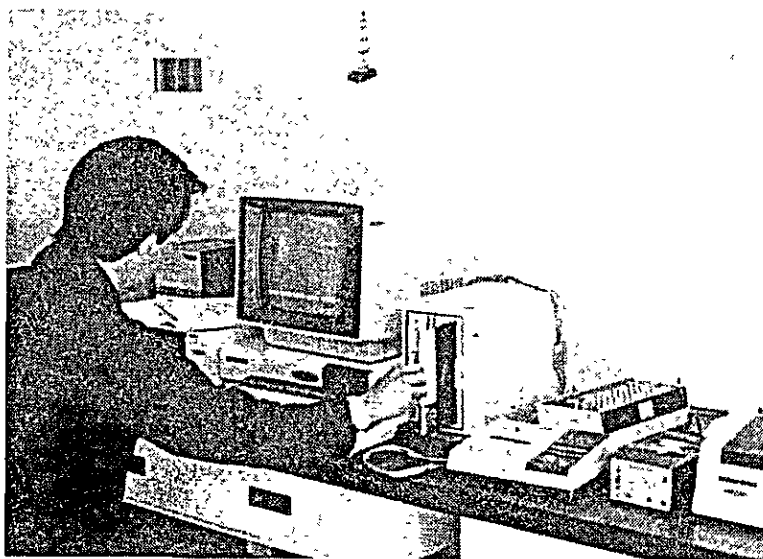


Foto-10 Experto Kenichiro Hayashi encargado de las prácticas de ciencia y tecnología.



### 3.2.2 Cursos

Los cursos fueron dictados semanalmente y tuvieron una duración de 2 horas diarias por materia entre el 16 de marzo al 17 de junio de 1982.

Los lecciones por materia, horario de clases, y expertos encargados están indicados en el cuadro 1. Tres clases de los días martes sobre "Análisis químico y aparatos de análisis fueron sustituidas por "fluorescencia de rayos X".

Las dos primeras clases del día jueves sobre "Análisis térmico y estudio de inclusiones fluidas fueron dictadas por el experto Dr. Nambu; posteriormente fueron continuadas por el Dr. Hayashi.

Los cursos de "Geología Económica y microscopia de opacos" consideraron la termodinámica. Este curso fue dado por el Jefe asesor Dr. Kano.

La fecha de cada lección, materia y lista de alumnos es indicada en el Cuadro-2. El número de lecciones entre marzo y junio de 1982 fue de un máximo de 12 y un mínimo de 9 veces.

El número de participantes máximo fué 11; los participantes fueron además de los profesores de Instituto de Geología Económica de otros institutos como Geodinámica y Limnología, y Geología Aplicada.

Los expertos encargados de los cursos prepararon textos en idioma inglés.

Se adjunta los mismos, así como un resumen de la materia dictada. Estos textos sirvieron de base para el conocimiento y estudio de la contraparte boliviana.

Cuadro-1 Materias y encargados de los cursos

PROGRAM OF FUNDAMENTAL LECTURE

|     |  |                            |
|-----|--|----------------------------|
| MON | PETROLOGY AND PETROGRAPHIC MICROSCOPY                            | DR.S.NAKADA                |
| TUE | CHEMICAL ANALYSIS FOR ROCKS AND MINERALS,<br>AND ITS INSTRUMENTS | DR.T.MIZOTA                |
| WED | X-RAY ANALYSIS FOR MINERALS                                      | DR.T.MIZOTA                |
| THU | THERMAL ANALYSIS, AND LIQUID INCLUSION<br>STUDY                  | DRS.M.NAMBU &<br>K.HAYASHI |
| FRI | ECONOMIC GEOLOGY AND ORE MICROSCOPY                              | DR.S.KANO                  |



Cuadro-2 Fechas de clases, materia lista de participantes

ATTENDANCE TABLE

Petrology and petrographic microscopy(by S.Nakada)

| DATE       | 21 | 28 | 4  | 11 | 18 | 25 | 9  | 16 | 23 | 30 | 14 | 20 |
|------------|----|----|----|----|----|----|----|----|----|----|----|----|
| MONTH      | MC | MC | AP | AP | AP | AP | MY | MY | MY | MY | JN | JN |
| A.Saavedra | o  | o  | -  | o  | o  | o  | o  | o  | o  | -  | -  | o  |
| O.Sanjines | -  | -  | -  | -  | o  | o  | o  | o  | o  | -  | o  | o  |
| M.Arduz    | o  | -  | -  | -  | o  | o  | -  | -  | -  | -  | -  | -  |
| A.Sanchez  | o  | o  | o  | -  | o  | o  | o  | -  | -  | -  | o  | o  |
| O.Velarde  | -  | -  | -  | -  | o  | -  | -  | o  | o  | o  | o  | -  |
| H.Villena  | o  | o  | o  | o  | -  | o  | -  | -  | o  | o  | o  | o  |
| G.Beccar   | -  | o  | -  | o  | -  | o  | o  | o  | -  | -  | -  | -  |
| F.Saavedra | o  | o  | o  | o  | -  | o  | o  | o  | o  | o  | o  | o  |
| E.Soria    | -  | -  | o  | o  | o  | o  | o  | o  | -  | o  | o  | -  |
| G.Sandi    | o  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |

Chemical analysis for rocks and minerals, and its instrument (by T.Mizota)

| DATE       | 22 | 29 | 5  | 12 | 19 | 26 | 10 | 17 | 24 | 7  | 14 |
|------------|----|----|----|----|----|----|----|----|----|----|----|
| MONTH      | MC | MC | AP | AP | AP | AP | MY | MY | MY | JN | JN |
| O.Sanjines | o  | o  | o  | o  | o  | o  | o  | o  | -  | o  | o  |
| M.Arduz    | o  | -  | o  | o  | o  | -  | -  | -  | -  | -  | -  |
| A.Sanchez  | o  | -  | o  | o  | o  | o  | o  | -  | o  | o  | o  |
| O.Velarde  | o  | -  | o  | o  | -  | o  | o  | -  | o  | o  | o  |
| H.Villena  | -  | o  | o  | o  | -  | o  | o  | -  | o  | o  | o  |
| G.Sandi    | o  | o  | -  | -  | o  | o  | o  | o  | o  | o  | o  |

\* X-ray fluorescence analysis lecture(24 May to 14 Jun)

X-RAY ANALYSIS FOR MINERALS(by T.Mizota)

| DATE         | 16 | 23 | 6  | 13 | 20 | 27 | 4  | 18 | 25 | 1  | 8  | 15 |
|--------------|----|----|----|----|----|----|----|----|----|----|----|----|
| MONTH        | MC | MC | AP | AP | AP | AP | MY | MY | MY | JN | JN | JN |
| O.Sanjines   | o  | o  | o  | o  | o  |    |    | o  | o  | o  | o  | o  |
| A.Sanchez    | o  | o  | o  | o  | o  |    |    | -  | o  | -  | o  | o  |
| O.Velarde    | o  | o  | -  | o  | o  |    |    | -  | -  | -  | o  | o  |
| H.Villena    | o  | o  | o  | -  | o  |    |    | -  | o  | -  | o  | o  |
| F.Saavedra   | o  | o  | -  | -  | -  |    |    | -  | -  | -  | o  | o  |
| G.Sandi      | -  | o  | o  | o  | o  |    |    | -  | o  | o  | o  | o  |
| R.Condoretti | o  | o  | -  | -  | -  |    |    | -  | -  | -  | -  | -  |
| J.Muñoz R.   | -  | o  | o  | -  | -  |    |    | -  | o  | -  | -  | -  |

MC:March, AP:April, MY:May, JN:June

(continued)

Thermal analysis, and liquid inclusion study (by M.Nambu and K.Hayashi)

| DATE        | 17 | 18 | 9  | 22 | 23 |
|-------------|----|----|----|----|----|
| MONTH       | MC | MC | JN | JN | JN |
| O.Sanjines  | o  | o  | o  |    |    |
| A.Sanchez   | -  | -  | o  |    |    |
| H.Villena   | -  | -  | o  |    |    |
| G.Sandi     | o  | o  | o  |    |    |
| J.Munoz R.  | o  | o  | -  |    |    |
| L.A.Rodrigo | o  | o  | -  |    |    |
| F.Saavedra  | -  | -  | o  |    |    |

\* 17 and 18 March by M.Nambu

Ore microscopy (by K.Hayashi)

| DATE       | 28 | 12 | 19 | 26 |
|------------|----|----|----|----|
| MONTH      | AP | MY | MY | MY |
| A.Saavedra | o  | o  | o  | o  |
| O.Sanjines | o  | -  | -  | o  |
| A.Sanchez  | o  | -  | -  | o  |
| F.Saavedra | o  | o  | o  | o  |
| G.Sandi    | o  | o  | o  | o  |

Economic Geology (by S.Kano)

| DATE        | 25 | 8  | 15 | 22 | 6  | 13 | 20 | 27 | 3  | 10 |
|-------------|----|----|----|----|----|----|----|----|----|----|
| MONTH       | MC | AP | AP | AP | MY | MY | MY | MY | JN | JN |
| A.Saavedra  | o  | o  | o  | o  | o  | -  | o  | -  | -  | -  |
| O.Sanjines  | o  | o  | o  | o  | o  | o  | o  | o  |    | o  |
| A.Sanchez   | o  | o  | o  | o  | o  | -  | -  | o  |    | o  |
| O.Velarde   | o  | -  | o  | o  | -  | -  | -  | -  |    | o  |
| H.Villena   | o  | -  | o  | -  | -  | -  | -  | -  |    | -  |
| G.Beccar    | o  | o  | -  | o  | o  | -  | -  | -  |    | -  |
| F.Saavedra  | o  | o  | o  | o  | o  | o  | o  | o  |    | o  |
| G.Sandi     | o  | o  | o  | o  | o  | -  | -  | o  |    | o  |
| L.A.Rodrigo | o  | -  | -  | -  | -  | -  | -  | -  |    | o  |
| F.Blanco    | o  | -  | -  | -  | -  | -  | -  | -  |    | -  |
| J.Munoz R.  | o  | -  | -  | -  | o  | o  | o  | o  |    | o  |

## Petrology and petrographic microscope

Setsuya Nakada

### Outline of lecture entitled "Petrology and petrographic microscope"

These 12 times lectures were held by Dr. S. Nakada from March 21 to May 20, 1983. Optical principles and the operation of petrographic microscope were mainly covered. The classifications of igneous rocks, phase petrology, geochemistry of igneous rocks were also lectured. The content is as follows.

- 1st: Japanese Quaternary volcanic rocks (including self-introduction)
- 2nd to 4th: Optical principles of petrographic microscope
- 5th: Calculating method of C.I.P.W. norm
- 6th: Classification of volcanic rocks and phase petrology(1)
- 7th to 8th: Phase petrology(2 to 3)
- 9th: Phase petrology(4) and stereographic projection(1)
- 10th: Stereographic projection(2) and classification of granitic rocks(1)
- 11th: Classification granitic rocks(2) and geochemistry of igneous rocks(1)
- 12th: Geochemistry of igneous rocks(2)

The text appearing below is a digest of optical principles of petrographic microscope, the immersion method, a method how to use the universal stage, an easy experimental method to determine the composition of plagioclase, and the calculating method of C.I.P.W. norm. Two Japanese books(Tsuboi, S.(1959), Polarized microscope, Iwanami Shoten, 305p; Miyashiro, A. and Kushiro, I.(1975), Petrology II; Kyoritsu Zensho, 171p) were referred to summarize it.

## Preface

We know that the petrographic microscope (polarized microscope) is very useful instrument for the study of fine solid materials in the field of petrology. The petrographic microscope is so basic that we can not start to study petrology without the instrument and the knowledge on optical principle. We can also identify some minerals by other methods; such as chemical analysis, X-ray analysis etc. By optical observation, however, we can easily and rapidly determine very fine minerals, small parts, inclusions and rock texture. The information on rock texture or structure observed under the microscope is very important. Through that we can understand the condition in which the rock or the mineral was formed. By mineral composition or by the chemical composition of rock, we can not speculate where a given igneous rock was formed. Therefore, even if many useful and convenient instruments are invented, we must continue to use the petrographic microscope as the most basic and important instrument for petrology and mineralogy.

## Optical principles

### 1) Introduction

Optically transparent materials are divided into two varieties: isotropic (cubic and amorphous) and anisotropic materials. Furthermore the anisotropic materials are classified into uniaxial and biaxial substances. Within the anisotropic substances, a light from one source separates into two independent polarized lights, with velocities of which are different, and for which the directions of their oscillation are normal to each other.

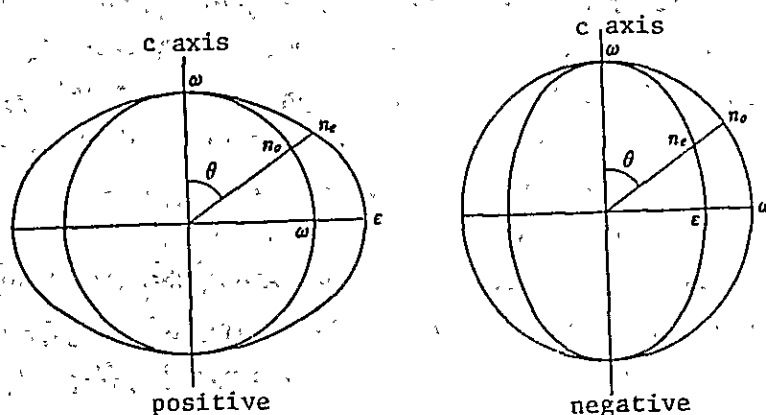


Fig.-1 Index surface of uniaxial crystal

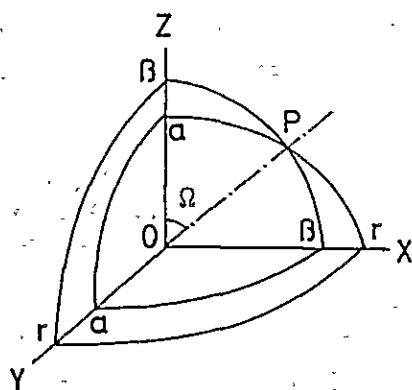


Fig.-2 Index surface of biaxial crystal

## 2). Index surface

The INDEX SURFACE is very important for us to observe minerals under the microscope. The INDEX SURFACE represents refractive indices in any directions from one point in a given substance. In the case of uniaxial crystal, we can draft the INDEX SURFACE as shown in Figure-1. In the anisotropic materials, there are two distinct refractive indices in each direction. This phenomenon is called DOUBLE REFRACTION or BIREFRINGENCE. The degree of the BIREFRINGENCE is represented as " $n_1 - n_2$ ": difference of two indices in a given direction. On the other hand, the direction in which there is no double refraction is called OPTIC AXIS. "Optically uniaxial" means that the material has one optical axis, while "optically biaxial" means two optical axes in the material. Optic axis in a uniaxial crystal is always parallel to the c-axis of the crystal. The index surface of biaxial crystals can be drawn as shown in Figure-2. This is more complex than that of uniaxial crystals. Figure-2 shows the eighth of the index surface. Here, X, Y and Z are the optical elasticity axes.  $\alpha$ ,  $\beta$  and  $\gamma$  are principal refractive indices ( $\alpha < \beta < \gamma$ ).  $2\Omega$  is optical angle ( $2V$  or  $180^\circ - 2V$ ) or optic axial angle. If  $2\Omega$  is greater than  $90^\circ$ ,  $180 - 2\Omega$  is the angle  $2V_x$  (negative). When  $2\Omega$  is smaller than  $90^\circ$ , the character is positive ( $2V_z$ ). Axes X and Z in Figure-2 mean bisectrix of optic axial angle. The plane including two optic axes is called OPTIC AXIAL PLANE. The angle  $\Omega$  is represented by  $\alpha$ ,  $\beta$  and  $\gamma$  as follows,

$$\sin \Omega = \frac{\gamma}{\beta} \sqrt{\frac{(\beta + \alpha)(\beta - \alpha)}{(\gamma + \alpha)(\gamma - \alpha)}}, \quad \cos \Omega = \frac{\alpha}{\beta} \sqrt{\frac{(\gamma + \beta)(\gamma - \beta)}{(\gamma + \alpha)(\gamma - \alpha)}}$$

$$\text{and } \tan \Omega = \frac{\gamma}{\alpha} \sqrt{\frac{(\beta + \alpha)(\beta - \alpha)}{(\gamma + \beta)(\gamma - \beta)}}$$

3) Vibration direction of polarized light in uniaxial crystal

Extraordinary light vibrates within a plane including its advancing direction and optic axis, and perpendicular to the advancing direction (Figure-3). Ordinary light vibrates perpendicular to both of the above plane and the advancing direction. Usually the vibration direction of the faster light is referred to as "X", while that of the slower one as "Z". We can easily determine such vibration direction under the microscope. To determine the direction of X or Z is much important for the determination of refractive index or optic sign of crystal.

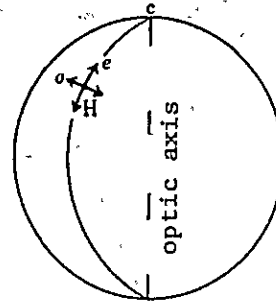


Fig.-3 Biot-Fresnel's rule for uniaxial crystal

4) Vibration direction of polarized light in biaxial crystal

According to the Biot-Fresnel's rule, we can find vibration direction of a polarized light which passes through one point on index surface (Figure-4).

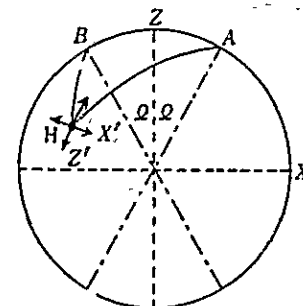


Fig-4 Biot-Fresnel's rule for biaxial crystal

1. Consider one direction H of an advancing light.
2. Consider two great circles connecting the direction H with optic axis A and B stereographically.

3. Here, we get a spherical triangle ABH. Slow polarized light Z' vibrates in the direction of bisectrix of angle ABH facing optic elasticity axis Z. Faster polarized light X' vibrates in the direction of bisectrix of the external angle of H, and also perpendicular to Z'.

Here, we can obtain the definitions of the optic elasticity axes; that is, the vibration direction of the fastest light is the direction of the optic elasticity axis X, and the vibration direction of the slowest light is the direction of Z. The direction perpendicular to the both is that of Y. In Figure-5, vibration direction of lights passing through the planes XY, YZ and ZX is shown.

Uniaxial positive crystal is regarded as biaxial positive crystal with  $2V_z=0^\circ$ , while uniaxial negative crystal is as biaxial negative crystal with  $2V_x=0^\circ$ . Vibration direction of polarized lights in uniaxial crystal can be also determined with the Biot-Fresnel's rule (Figure-3). In this case, an interior angle of spherical triangle (AHB in Figure-4) would be zero.

#### 5) Optical orientation

Optical orientation in a crystal means the relation of optic elasticity axis, optic axis and crystal axis. Tetragonal and hexagonal crystals belong to uniaxial group. In orthorhombic crystal, each optic elasticity axis is parallel to each crystal axis. In monoclinic crystal, one optic elasticity axis is parallel to one of the crystal axes. In triclinic crystals, the optic elasticity axes are independent of the crystal axes.

#### 6) Observation of optically anisotropic crystal under the microscope

When we observe optically anisotropic crystals under crossed nicols, we observe four times of darkness during one rotation of the microscopic stage. This phenomenon of darkness is called EXTINCTION. The angle between two extinction positions is  $90^\circ$ . The position where the stage is rotated at  $45^\circ$  from the extinction position is called DIAGONAL POSITION.

Let's consider a light coming toward us perpendicular to this paper. PP' and QQ' are vibration directions of polarizer and



analyzer, respectively, in Figure-6.

AA' and BB' represent vibration directions of faster and slower lights, respectively, in thin section. The angle between AA' and PP' is  $\theta$ . When a polarized light with the amplitude of A enters into a polar, generally, the amplitude of the passed light is represented by  $A\cos\theta$ : that is, when  $\theta$  is zero, whole light can pass through, while the light is intercepted by the polar when  $\theta=90^\circ$ . An amplitude of the vibration of the transmitted light is determined by simple "vector principle" which is employed in the resolution of forces. A polarized light vibrating in the direction of PP' separates into new two polarized lights in an anisotropic material. The two vibrate in the direction of AA' and BB'. If the amplitude of source-light is OP, the amplitude of polarized lights AA' and BB' are OA and OB respectively. After passing through the anisotropic material, the components of the two lights in the direction QQ' can only pass through the analyzer. The amplitudes are OQ and OQ'.

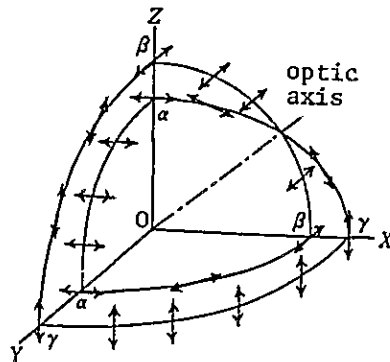


Fig.-5 Vibration direction of lights and index surface of biaxial crystal

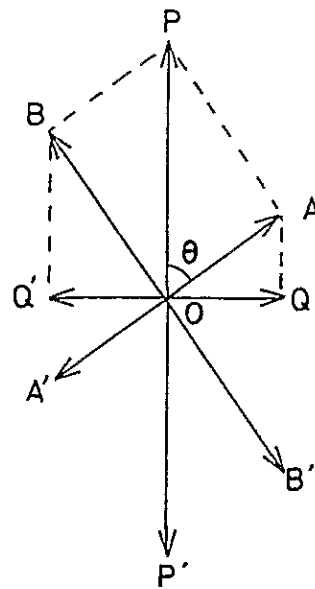


Fig.-6 Relationship of vibration directions between nicols and mineral

Amplitude of the synthesized wave which we can observe is written as,

$$A'^2 = A^2 \sin^2 2\theta \sin^2 [\pi d(n_2 - n_1) / \lambda_0]$$

Where A is an amplitude of source-light, d is thickness of thin section, and  $\lambda_0$  is wave length of light in air.  $A'^2$  represents the brightness of the synthesized wave. The way to introduce this equation is not so difficult, but this explanation is omitted here. This equation is very important.

When  $\theta$  is  $0^\circ$ ,  $\pi/2$ ,  $\pi$ ...,  $\sin^2 2\theta = 0$  and  $A'^2 = 0$

This is in the extinction condition.

When  $\theta$  is  $\pi/4$ ,  $3\pi/4$ ,  $5\pi/4$  ...,  $\sin^2 2\theta = 1$  and  $A'^2 = \text{maximum}$ .

This is the diagonal position.

Furthermore, when  $\theta$  is constant, the brightness is determined by " $d(n_2 - n_1)$ " and wave length of the source-light.

When  $d(n_2 - n_1) = p\lambda_0$ ,  $A'^2 = 0$

When  $d(n_2 - n_1) = (2p+1)\lambda_0/2$ ,  $A'^2 = \text{maximum}$ .

(where  $p=1, 2, 3$  ...)

We will now consider about how long the slow polarized light is delayed against the fast polarized light during the passage in anisotropic materials. Thickness of thin section is d, and wave lengths of polarized lights are  $\lambda_1$  and  $\lambda_2$  for the fast and slow lights respectively. The fast light passes through the thin section by the oscillation of  $d/\lambda_1$  times, and the slow light does by  $d/\lambda_2$  (Figure-7). The latter is delayed by the oscillation of  $d(1/\lambda_2 - 1/\lambda_1)$  times against the former. When the slow light goes out of the thin section, the fast light advances by the distance of  $\lambda_0(d/\lambda_2 - d/\lambda_1)$ . This term means the retardation distance of the slow light against the fast light in the section. This is called RETARDATION of thin section or crystal. Since  $\lambda_0/\lambda_2 = n_2$  and  $\lambda_0/\lambda_1 = n_1$ , we can write this term as  $R = d(n_2 - n_1)$ . This was already understood in the representation of the brightness of light passing through thin section under crossed nicols. Retardation is represented in  $m\mu$ . For example, consider a thin section with

$R/\lambda_0 = 1$  by blue-colored light ( $\lambda_0 = 460 \text{ m}\mu$ ). In this case, the brightness of the blue-colored light in this section is zero; that is, the blue-colored light disappears in the section. However, other lights with wave length different from  $460 \text{ m}\mu$  (for example, yellow- and red-colored lights) do not disappear. When the thin section is observed by white light, the INTERFERENCE COLOR is observed to be mixed color of yellow and red.

Generally we can refer to retardation of thin section or maximum birefringence in a crystal with the interference color chart of "michel-Levy". When colored minerals are observed under crossed nicols, the color of the mineral must be taken into consideration. When a color different from the interference color chart is observed after the above treatment, the color is called ANOMALOUS INTERFERENCE COLOR or ABNORMAL INTERFERENCE COLOR. The reason why anomalous interference color appears, is changeable retardation of the mineral depending on wave lengths of a source-light.

#### 7) How to determine the directions of X' and Z'

To determine the vibration direction of two polarized lights in thin section of a given mineral, we move the section to the extinction position under crossed nicols. Because the extinction results from the coincidence of vibration direction of polarized light through the mineral with that of analyzer or polarizer.

To determine whether the vibration direction is X' or Z', we may apply the principle of putting a thin section upon another; that is, the usage of test plate.

After a mineral is moved into the diagonal position (one of the vibration directions is NE), the test plate is inserted. "If X' and Z' of the mineral are parallel to those of the test plate, we observed the interference color by adding two retardations (mineral and test plate). If X' and Z' of the mineral coincide with Z' and X' of the test plate, respectively, the interference color is given by the subtraction of the two retardations." Thus,

we can easily determine  $X'$  and  $Z$ ; in a given mineral in thin section.

8) Optical sign of elongation

The angle between the conspicuous outline of the mineral and one of the vibration direction is called the extinction angle  $\eta$  (Figure-8). When  $\eta=90^\circ$  or  $0^\circ$ , the section shows STRAIGHT EXTINCTION. When  $\eta$  is not equal to  $0^\circ$  or  $90^\circ$ , the section shows OBLIQUE EXTINCTION.

When a mineral is elongated in one direction and shows the straight extinction in a thin section, we usually use terms of NEGATIVE ELONGATION or POSITIVE ELONGATION. This term is different from the optical character of crystal. When the direction of the elongation is parallel to  $Z'$ , we say that the mineral shows positive elongation. The contrary means negative elongation.

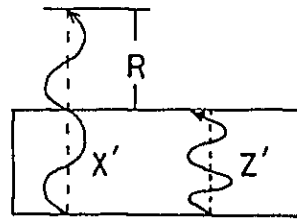


Fig. 7 Schematic illustration of retardation

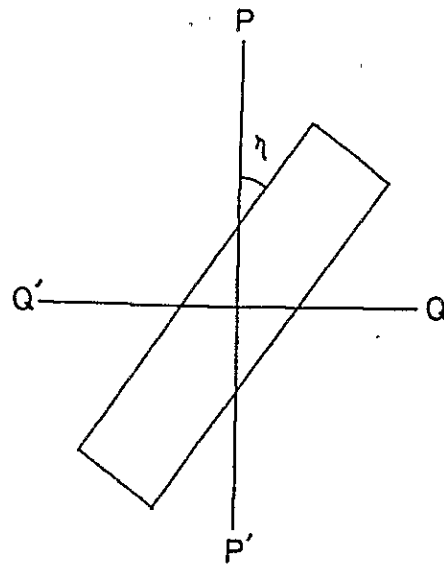


Fig. 8 Oblique extinction

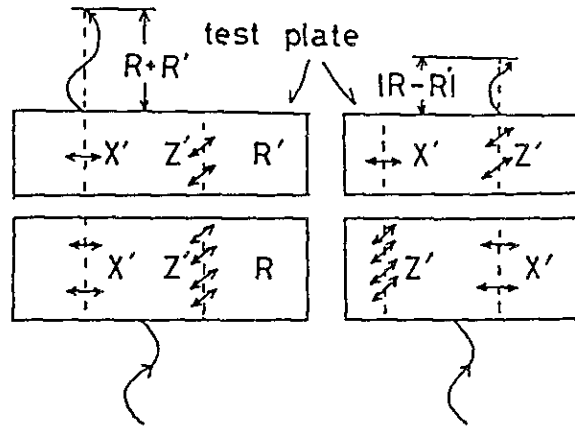
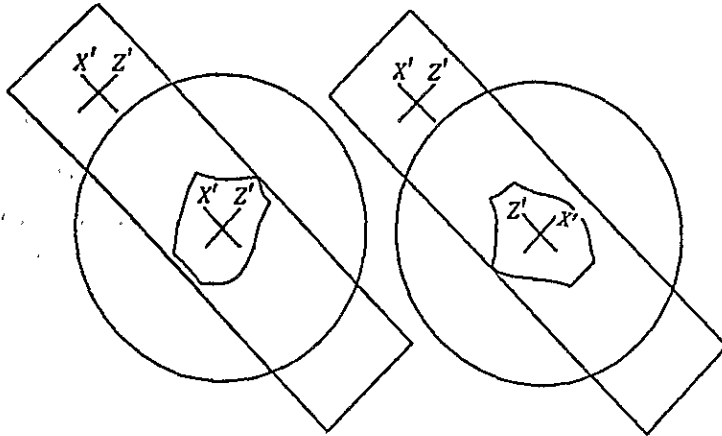


Fig.-9 Addition and subtraction relation of retardations between test plate and mineral. This is important to determine the vibration directions of  $X'$  and  $Z'$ . Left: addition, and right: subtraction.

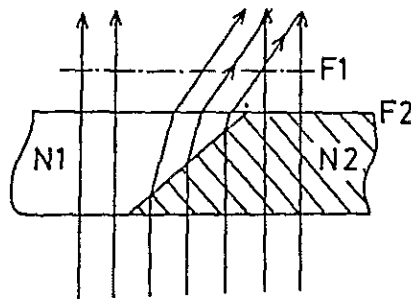


Fig.-10 Ray refraction along a boundary of two substances with different refractive indices ( $N_2$  is greater than  $N_1$ ). Upward moving of focus from  $F_2$  to  $F_1$  causes moving of bright zone (represented by arrows with narrow intervals) to the right-hand side.

9) Rule of Becke's line(Becke line)

We can observe a little bright line or zone along the boundary between the minerals in thin section under the microscope, especially when light is stopped down. This line is called BECKE'S LINE or BECKE LINE. By the usage of this line, we can assign which mineral or substance has higher refractive index. "The increase of the distance between the thin section and the objective lens results the movement of the Becke's line into the material with higher refractive index(Figure-10). On the other hand, the decrease of the distance causes the movement into the mineral with lower refractive index." This rule is applied also to measuring refractive index by the immersion method.

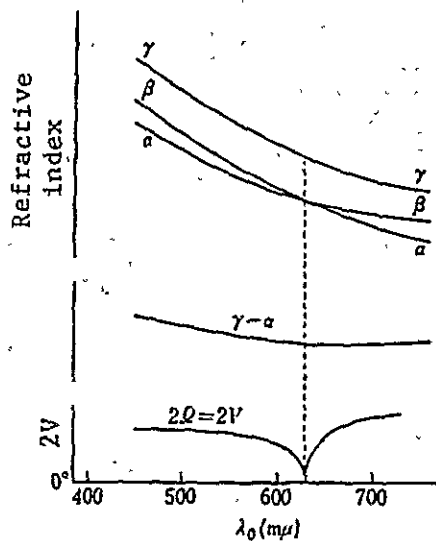


Fig.-11a Dispersion of refractive indices, birfringence and  $2V$  in a biaxial crsystal

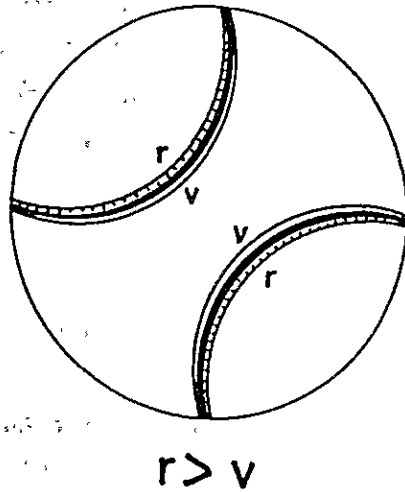


Fig.-11b Conoscopic figure of a biaxial crystal. Red-colored isogyres show greater  $2V$  than violet-colored isogyres, indicating that  $2V$  for red-colored light is smaller than for violet-colored light.

#### 10) Optical dispersion

Depending on the difference of wave length, the optical orientation or character in mineral may change(Figure-11a). This phenomenon is called OPTICAL DISPERSION. The change of the orientation in optic axis may occur(optic axial dispersion). If  $2V$  for red-colored light is larger than the angle for violet-colored light, the phenomenon is described as  $r < v$ (Figure-11b). The reverse case is  $r > v$ .

#### 11) Pleochroism and absorption

When a light passes through a medium, it is absorbed and the brightness reduced. The degree of the absorption depends on the kind of minerals, and on the wave length of used light. For example, when a material absorbs a red-colored light, the material is colored in blue under white light.

In an isotropic material, the degree of the absorption is equal in any direction. Therefore, color of the isotropic material

is equal in any direction under white light. In the case of the anisotropic material, two polarized lights advancing in one direction suffer different degrees of absorption. A light vibrating along  $X'$  shows different color from that shown by a light vibrating along  $Z'$ . This character is called PLEOCHROISM.

We can assign the color of the light vibrating along  $X'$  and  $Z'$  by taking off the analyzer and by fitting  $X'$  or  $Z'$  of the crystal with the vibration direction of polarizer.

In the case of biaxial mineral, we always describe the colors of light vibrating along the optic elasticity axes,  $X$ ,  $Y$ , and  $Z$ . The color is called AXIS COLOR. We describe the axis color of  $Z$  for amphibole, for example, because the description of amphibole is always expressed with pleochrosim ( $Z$  axial color) and with extinction angle ( $c\wedge Z$  or  $c\wedge X$ ).

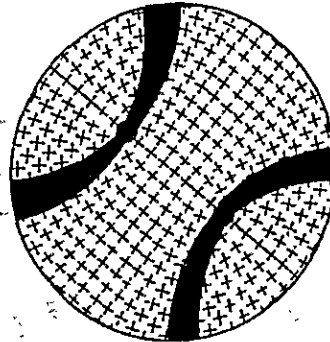


Fig.-12 One example of conoscopic figure and vibration directions of  $X'$  and  $Z'$  in each point of biaxial crystal. This crystal is cut perpendicular to  $Z$  (or  $X$ ).

## 12) Conoscopic figure

In orthoscopic figure, parallel ray passes through perpendicular to a thin section. In conoscopic figure, however, we observe the convergent light passing through a thin section.

Normally the conoscopic figure is magnified by both of bertrand



and eyepiece lenses. We use ray inclining by  $30^\circ$  as maximum from the central axis of microscopic tube in conosopic figure, while orthoscopic figure is observed with the parallel ray normal to the thin section. The latter is represented only by central point in conosopic figure.

The conosopic figure is composed of ISOCHROMATIC CURVES and ISOGYERS. The isochromatic curves appear due to the same reason as interference colors in the orthoscopic figure. That is; each isochromatic curve represents the trace of the same retardation. The isogyers are explained by the same phenomenon with the extinction in the orthoscopic figure. The points where vibration directions of lights coincide with those of polarizer and analyzer, are dark, being independent on the degree of retardation of them. The mode of isogyer for every section can be easily understood with the Biot-Fresnel's rule stereographically (Figure-12). MELATOPE is a point in the isogyer, which represents the direction of optic axis ( $R=0$ ). Without melatope in conosopic figure, it is very difficult to determine the character (biaxial positive or negative) of the mineral. When  $2V$  is very small, we apt to misunderstand that the mineral is uniaxial. For example, sphene has very small  $2V$ , and the conosopic figure resembles very much to that of uniaxial crystal.

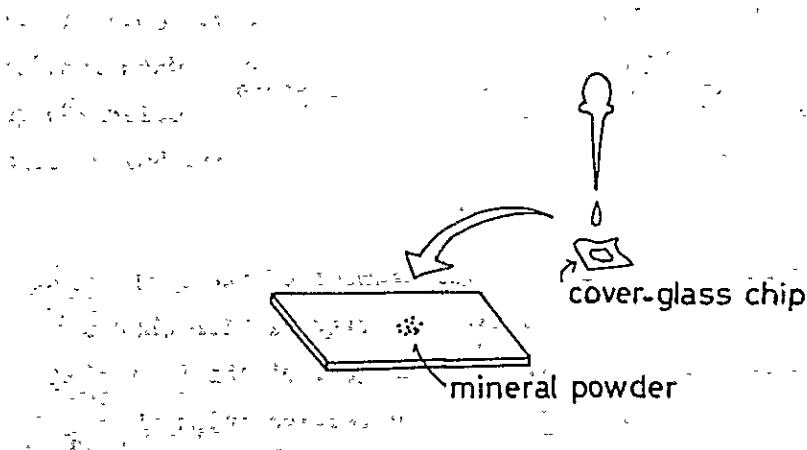
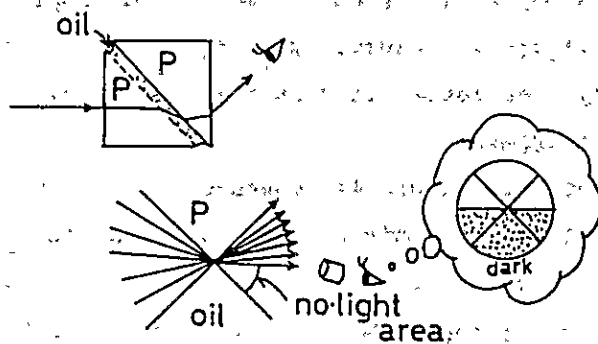
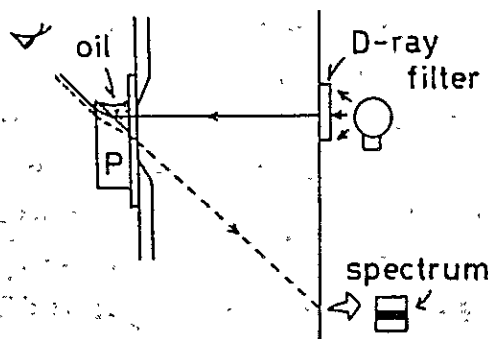


Fig.-13 Illustration of immersion method



ABBE TYPE



K TYPE

Fig.-14 Mechanism of refractometers

Immersion method

The immersion method permits measurement of the refractive index by comparing refractive index of a crystal with that of liquid with known refractive index. The goal of the immersion method is to find a liquid with known refractive index which matches that of the unknown crystal.

1) In case of optically isotropic substance

Refractive index of the optically isotropic substance does not vary in any direction, but varies depending on wave length of light used.

(a) Fragments of the substance are powdered in a mortar.

A little amount of the powder is dispersed on a glass slide.

(b) On the chip of cover glass, immersion liquid\* is dropped.

The chip is turned upside down and covers the powder on the glass slide (Figure-13). The powder must be immersed in the liquid between the two glasses.

\*Many immersion liquids with variable refractive indices must be prepared and measured with the refractometer (Abbe type or K type), before use. Abbe type refractometers cannot measure refractive indices larger than 1.700.

The mechanisms of these refractometers are shown in Figure-14. Refractive index of the immersion liquid depends on the temperature and wave lengths of the used light.

The liquid is prepared as a mixture of some kinds of heavy liquids. Since heavy liquids are very harmful to our health, we must pay our attention to the treatment. When we wash off the liquid from the prism of the refractometer, we must use a volatile solvent such as benzene ( $C_6H_6$ ), as shown in Figure-15. Do not mop up the prism by control wool! Do not use cover and slide glasses once wetted with the immersion liquid.

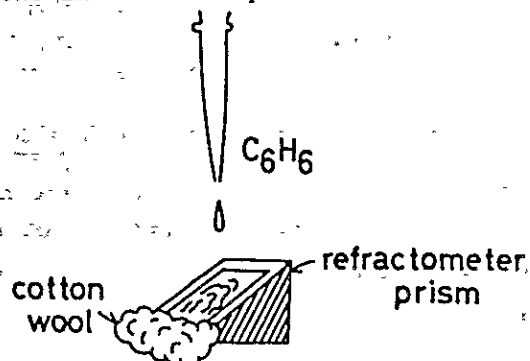


Fig.-15 Method of washing prism of the refractometer

- (c) Observing the Becke's line around the unknown crystal, we can compare the refractive indices of the crystal with those of the liquid.
- (d) Based on the result from (c), we try other liquids successively by the same way described in (a).
- (e) Even if we cannot find the liquid whose index is coincide with that of the crystal, we can determine that the index of the crystal is between indices of two liquids, which have very-near indices.

$$n' < n < n'' \text{ or } n = (n' + n'')/2 \pm (n'' - n')/2$$

By this method we can determine the index down to four decimal places (0.000X), if we use monochromatic light. In general, we may determine three figures (0.00X).

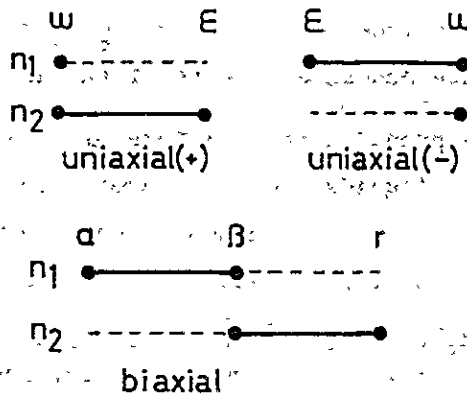


Fig.-16 Variational ranges of two refractive indices ( $n_1$  and  $n_2$ ) of uniaxial and biaxial crystals.

2) To determine the principal refractive indices  $\epsilon$  and  $\omega$ , or  $\alpha$ ,  $\beta$  and  $\gamma$ .

We find vibration directions,  $X'$  and  $Z'$ , of an anisotropic crystal, and we can measure  $n_1$  and  $n_2$  of the crystal. Turning the crystal into the extinction condition (one of vibration directions ( $X'$  or  $Z'$ ; that is,  $n_1$  or  $n_2$ ) is parallel to N-S), we observe the Becke's line.

(a) Uniaxial(positive) substance

$n_1$  is constant( $\omega$ ), not depending on the direction of crystal, while  $n_2$  varies from  $\omega$  to  $\epsilon$ .  $\epsilon$  is determined as the maximum value among the observed indices of  $n_2$ (Figure-16).

(b) Uniaxial(negative) substance

$n_2$  is constant( $\omega$ ), not depending on the direction of crystal, while  $n_1$  varies from  $\omega$  to  $\epsilon$ .  $\epsilon$  is determined as the minimum value among the observed indices of  $n_1$ .

(c) Biaxial substance

Both  $n_1$  and  $n_2$  vary in all directions of the crystal. The minimum value of  $n_1$  is  $\alpha$ , and the observed maximum value is  $\beta$ . On the other hand, the minimum value of  $n_2$  is also  $\beta$ , and the maximum value is  $\gamma$ .

$$n_1 \max = \beta = n_2 \min.$$

A crystal which is usually black under crossed nicols (Retardation is zero) directly gives the refractive index of  $\beta$ . Based on the determined indices, we can calculate  $2V$  of the crystal and the optic sign(see the chapter of index surface of optical principle).

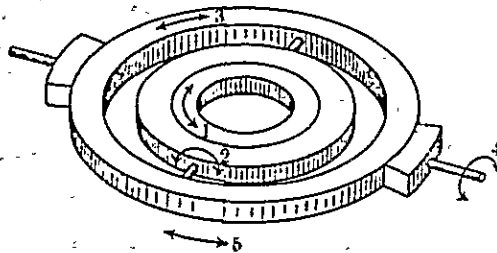


Fig.-17a Construction of universal stage. 1: inner vertical axis, 2: N-S axis, 4: E-W axis, and 5: rotation of microscopic stage.

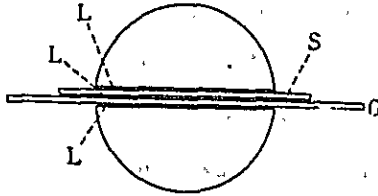


Fig.-17b Thin section sandwiched between two glass hemispheres.  
 L: immersion oil or glycerin, S: thin section, and  
 G: glass plate

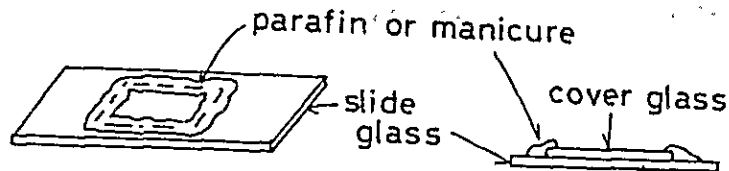


Fig.-18 Illustration of treatment of thin section to protect  
 glasses from oil in the universal state.

#### Universal Stage

As the stage of microscope rotates within one plane, optic character of a crystal perpendicular to the stage is only able to be known. However, as the thin section rotates around more than three axes in the universal stage, we can determine the character in any direction of the crystal. The main structure of the universal stage is shown in Figure-17. There are four circles, 1, 2, 3, and 4, which can rotate independently. Thin section is put between two glass hemispheres in the center, being wetted with immersion oil or glycerine. All axes of rotation must intersect at one point at the center of the glass sphere. Available set of glass hemispheres is chosen, to obtain the refractive index near to that of the crystal in observation.

1) Setting thin section in the universal stage

As shown in Figure-18, edges and corners of cover glass on the thin section must be sealed with manicure or melted parafin to avoid damage of the glass hemisphere and to protect Canada balsam in thin section from oil. A thin section is set in the universal stages as shown in Figure-17. The centering must be done at first in the microscopic tube, and next in the inner vertical axis of the universal stage, and then in the east-west axis.

2) Measurement of the directions, X, Y and Z of a crystal

When a thin section rotates around the axis within a plane perpendicular to the microscopic tube, there are some rules as follows,

- (a) If the rotation axis is parallel to one of the optical elasticity axes, the extinction condition of the crystal is not disturbed by the rotation.
- (b) If the rotation axis is not parallel to any elasticity axis, the extinction condition of the crystal is always disturbed by the rotation.

Observing method in the universal stage is as follows,

1. Fasten the E-W axis of the universal stage parallel to the vibration direction of analyser(or polarizer).
2. Observed crystal is brought into the extinction condition by the rotation around the I.V. axis.
3. By using the E-W axis, the section is inclined into one side (the extinction is disturbed).
4. By using the N-S axis, the crystal is brought into the extinction condition.
5. By using the E-W axis again, the section is inclined into the side against the treatment in 3. The extinction condition is disturbed.

6. By the rotation around the I.V. axis, the section into the extinction condition.
7. By the E-W axis, the section is inclined into the side against the treatment of 5. The extinction out.
8. By the N-S axis, - - - .
9. By the E-W axis, - - - .

Like this, by the two rotations around the I.V. and N-S axes, the section is brought into the extinction orientation, while we check whether the extinction disappears or not by any rotation around the E-W axis.

Repeating this treatment, the extinction becomes to be not disturbed by any rotation around the E-W axis. Then, one of the elasticity axes is parallel to the E-W axis. This orientation can be read with the angles of the axes, I.V. and N-S. To determine which of the elasticity axes is parallel to the E-W axis, the test plate is inserted after turning the microscopic stage clockwise by  $45^\circ$  in the same condition (in the diagonal condition).

- (1) If the optic elasticity axis is X, additional condition of retardation is observed.
- (2) If the optic elasticity axis is Z, subtraction is.
- (3) If the optic elasticity axis is Y, both addition and subtraction conditions are observed during the rotation around the E-W axis.

After the determination of one elasticity axis, another axis is given by the same way (1 to 9). Last one axis is given diagrammatically on the stereogram.

### 3) Measurement of optic angle

According to the above method, Y axis is brought parallel to the E-W axis. After turning the stage at  $45^\circ$ , the section is rotated around the E-W axis. In this case, the crystal becomes



dark when the optic axis is parallel to the microscopic tube. If we observe two times of darkness during the one rotation of the E-W axis, the angle between the two darknesses is optic angle. The optic sign of the crystal is determined by the angle and the associated effect with test plate check. When we observe only one optic axis, we can determine diagrammatically the optic angle and sign, using the orientation of X or Z axis.

4) Correction of angles determined with the universal stage

Except for the case in which the refractive index of the glass hemisphere is consistent with that of crystal, the angle measured in the universal stage does not represent directly the angle of mineral. As shown Figure-19, we know the true value of angle( $\theta'$ ) from the measured value( $\theta$ ), using the equation:  $n\sin\theta = n'\sin\theta'$ . Generally this correction is not necessary when the refractive index of the used glass sphere is near that of the crystal and when the inclination angle of the section is smaller than  $30^\circ$ .

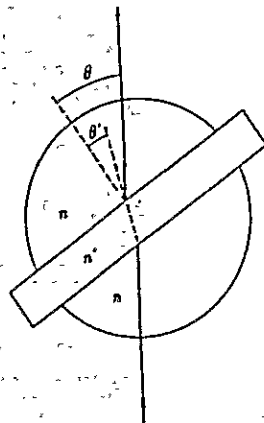


Fig.-19 Pass of light through glass hemispheres and thin section in universal stage. Refractive indices of glass and mineral are  $n$  and  $n'$  respectively.

Optical determination of plagioclase composition

Plagioclase is the most common mineral in igneous rocks. So, here, two convenient methods to determine the composition of plagioclase are explained.

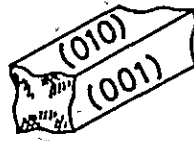


Fig.-20 Chip of plagioclase crushed in mortar.

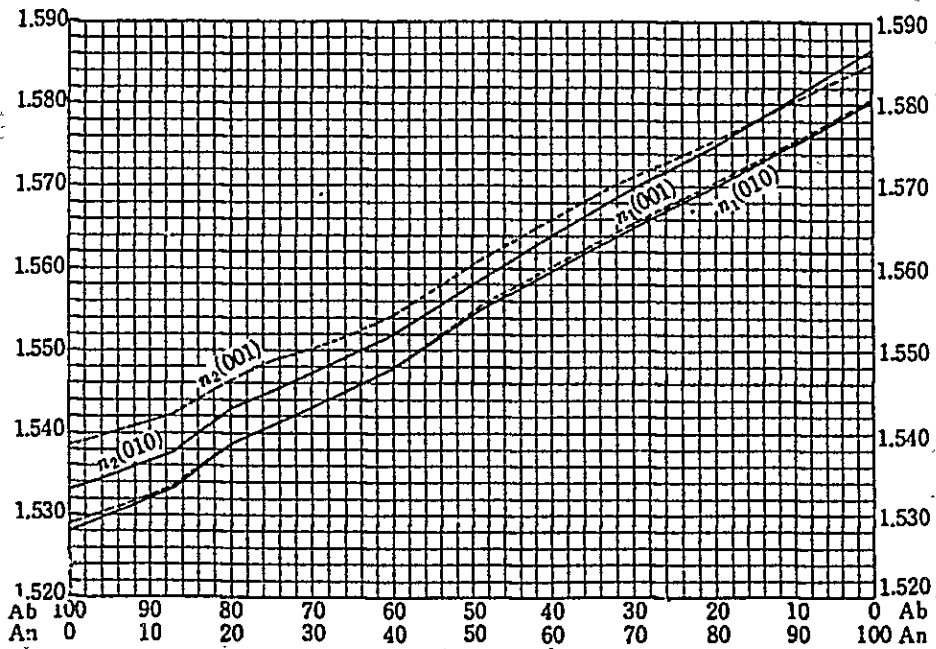


Fig.-21 Chemical composition(mol-ratio) of plagioclase and the refractive indices on cleavage planes. Dashed line is for high-temperature form. Solid line is for low-temperature form. After Tsuboi(1959); Polarized microscope, Iwanami-Shoten.

1) Refractive index of  $n_1$  on (010) or (001)

Cleavages of plagioclase are parallel to (001) and (010), as shown in Figure-20. The lower refractive index,  $n_1(X')$ , is nearly equal to each other on both cleavage planes (Figure-21). Using the chips surrounded by the cleavages, we can determine the composition in immersion method, without distinguishing (001) from (010). We measure the refractive index only of the fast light ( $X'$ ).

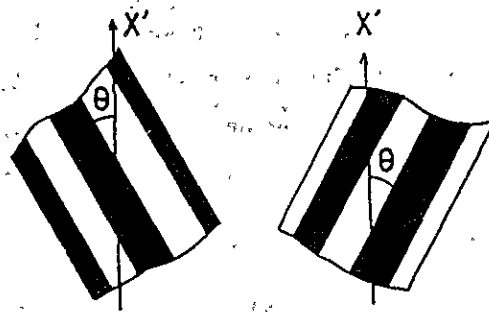


Fig.-22 Symmetrical extinction of plagioclase on the both sides of albite twin plane (010).

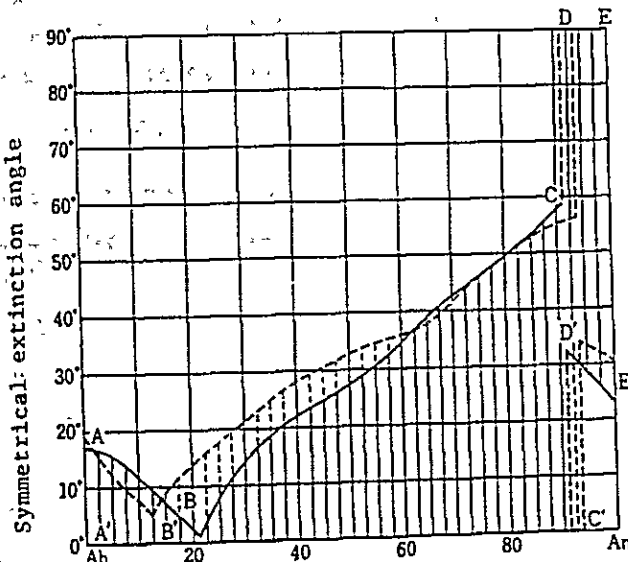


Fig.-23 Chemical composition of plagioclase (mol-ratio) and the extinction angle on the plane normal to (010) plane. Dashed line is for high-temperature form, while solid line is for low-temperature form. After Suwa et al. (1968); Proc. Japan Acad., 44, 1090-1095.

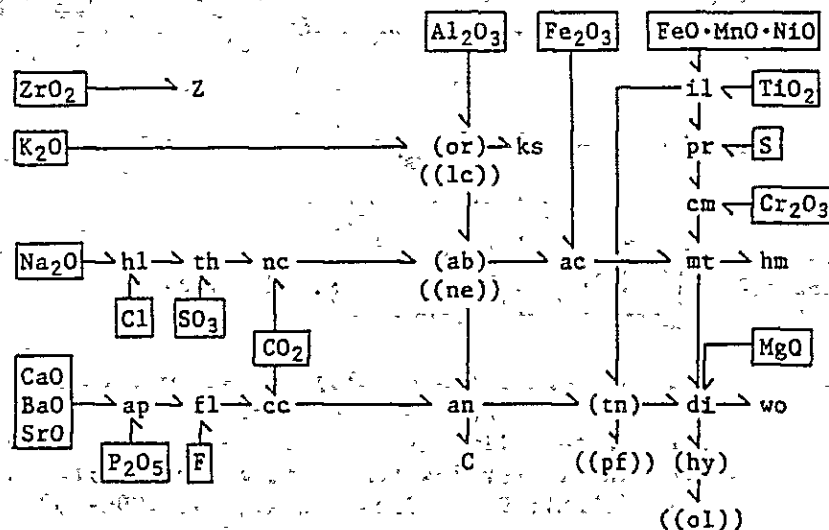
2) Maximum symmetrical extinction angle,  $X'\Lambda(010)$

Any section of albite-twinned plagioclase cut perpendicular to (010) shows two sets of twin lamellae having equal extinction angle,  $X'\Lambda(010)$ , in both side from the trace (010). But, if the section is cut not perpendicular to (010); that is, the trace of the cleavages is not sharp, the extinction angles in both sides are not equal. The symmetrical extinction angle varies with the orientation of cutting. The maximum angle has been determined in terms of the composition. We can easily obtain the condition in which cleavage (010) is parallel to the microscopic tube and perpendicular to the E-W axis in the universal stage. After setting the cleavage parallel to the tube, we determine maximum symmetrical angle by rotations around the E-W axis and the microscopic stage.

Calculating method of C.I.P.W. norm.

There are two calculating methods of normative minerals. One is C.I.P.W. norm which is very popular, and the other is Rittmann's which is used only in Europe. The latter is very complicated and includes many human operations, and may lose the original meanings of analysis. Here calculating method of C.I.P.W. norm is explained.

Table-1 Calculation method of C.I.P.W. normative minerals



Rules of the calculating method are composed of five parts.

### 1) Calculation of molecular amount

(a) Results of chemical analysis are usually given in wt% of oxides. Each oxide wt% must be divided by the molecular weight, and we obtain "molecular amount" of oxides.

(b) The very small amount of MnO and NiO were added to FeO (these oxides are not treated as independent components). When BaO and SrO were analyzed, the molecular amounts are also added to CaO.

(c) There is a rule in which a molecular amount of less than 0.002 can be negligible.

### 2) Calculation of accessory minerals

Among the normative minerals, at first we calculate amounts of minerals which occur rarely in igneous rocks.

(a) After addition of the molecular amount of  $\text{TiO}_2$  into the same amount of FeO, we make ilmenite ( $\text{FeO} \cdot \text{TiO}_2$ ). In normal case, FeO is greater than  $\text{TiO}_2$ . If  $\text{TiO}_2$  remains, we will obtain titanite ( $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$ ) after calculation of anorthite in 3).

(b) After addition of the molecular amount of  $\text{P}_2\text{O}_5$  into that of CaO by 3.3 times of  $\text{P}_2\text{O}_5$ , we make apatite ( $3(3\text{CaO} \cdot \text{P}_2\text{O}_5) \cdot \text{Ca} \cdot \text{F}_2$ ). We may not analyze F.

(c) When  $\text{Cl}_2$  was analyzed, we make halite ( $\text{Na}_2\text{Cl}_2$ ), adding the molecular amount of  $\text{Cl}_2$  into the same amount of  $\text{Na}_2\text{O}$ .

(d) When  $\text{SO}_3$  was analyzed, we make thenardite ( $\text{Na}_2\text{O} \cdot \text{SO}_3$ ), adding the molecular amount of  $\text{SO}_3$  into the same amount of  $\text{Na}_2\text{O}$ .

(e) When S (not  $\text{SO}_3$ ) was analyzed, we make pyrite ( $\text{FeS}_2$ ), adding the molecular amount of S into the same amount of O in FeO.

(f) When  $\text{Cr}_2\text{O}_3$  was analyzed, we make chromite ( $\text{FeO}\cdot\text{Cr}_2\text{O}_3$ ), adding the molecular amount of  $\text{Cr}_2\text{O}_3$  into the same amount of  $\text{FeO}$ .

(g) When F was analyzed, we make fluorite ( $\text{CaF}_2$ ), adding the molecular amount of F into the same amount of  $\text{CaO}$ , without being concerned about the O in  $\text{CaO}$ .

(h) When  $\text{ZrO}_2$  was analyzed, we get zircon ( $\text{ZrO}_2\cdot\text{SiO}_2$ ), adding the molecular amount of  $\text{ZrO}_2$  into the same amount of  $\text{SiO}_2$ .

(i) When  $\text{CO}_2$  was analyzed, we make calcite ( $\text{CaO}\cdot\text{CO}_2$ ) if the analyzed rock contains calcite, or sodium carbonate ( $\text{Na}_2\text{O}\cdot\text{CO}_2$ ), if the rock contains cancrinite.

### 3). Calculation of major minerals.

Using the molecular amounts of oxides which remain after the above procedures, we calculate major normative minerals.

(a) At first, we calculate orthoclase ( $\text{K}_2\text{O}\cdot\text{Al}_2\text{O}_3\cdot6\text{SiO}_2$ ). After this, there are two cases:  $\text{K}_2\text{O}$  remains or  $\text{Al}_2\text{O}_3$  remains. If  $\text{K}_2\text{O}$  remains (rare case), we calculate  $\text{K}_2\text{O}\cdot\text{SiO}_2$ . When  $\text{Al}_2\text{O}_3$  remains, go to next step.

(b) We make albite ( $\text{Na}_2\text{O}\cdot\text{Al}_2\text{O}_3\cdot6\text{SiO}_2$ ), adding a part or all of the residual  $\text{Al}_2\text{O}_3$  into  $\text{Na}_2\text{O}$ . When  $\text{Na}_2\text{O}$  remains, we go to the step (d).

(c) Next we make anorthite ( $\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot2\text{SiO}_2$ ), adding a part or all residual  $\text{Al}_2\text{O}_3$  into  $\text{CaO}$ . When  $\text{CaO}$  remains, we go to the step (e).

(d) When  $\text{Na}_2\text{O}$  remains, we make acmite ( $\text{Na}_2\text{O}\cdot\text{Fe}_2\text{O}_3\cdot4\text{SiO}_2$ ), adding it into a part of  $\text{Fe}_2\text{O}_3$ . Adding the residual  $\text{Fe}_2\text{O}_3$  into part or all of  $\text{FeO}$ , we obtain magnetite ( $\text{FeO}\cdot\text{Fe}_2\text{O}_3$ ). When  $\text{Fe}_2\text{O}_3$  remains, we make hematite ( $\text{Fe}_2\text{O}_3$ ). Normally,  $\text{FeO}$  remains.

(e) We often have the residual  $\text{CaO}$  in the step (c), and residual  $\text{FeO}$  in the step (d). These two oxides and  $\text{MgO}$  are used to make pyroxene and olivine. First, we calculate diopside

$(\text{CaO} \cdot (\text{Mg}, \text{Fe})\text{O} \cdot 2\text{SiO}_2)$ . Keeping the ratio of the residual FeO against MgO, we add FeO and MgO to CaO to make diopside ( $\text{CaO} = \text{FeO} + \text{MgO}$ ).

(f) When CaO remains after the above procedure, we make wollastonite ( $\text{CaO} \cdot \text{SiO}_2$ ). When FeO and MgO remain, we make hypersthene ( $(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$ ) and/or olivine ( $2(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$ ). The presence of hypersthene or olivine, or both, depends on the amount of residual  $\text{SiO}_2$ , which is explained below. We must calculate diopside, hypersthene and olivine, the ratios, FeO to MgO, of which are equal to each other.

#### 4) Partition of $\text{SiO}_2$ into the minerals

(a)  $\text{SiO}_2$  is partitioned into the accessory and the major minerals calculated above. However, in the calculation of the final step (f) in 3), we add  $\text{SiO}_2$  to all residues of MgO and FeO in order to obtain hypersthene. When  $\text{SiO}_2$  remains, we get quartz.

(b) When  $\text{SiO}_2$  is insufficient, we try to make olivine together with hypersthene, as described below. We consider the molecular amount of hypersthene as "hy" and that of olivine as "ol".

$$\text{hy} = 2(\text{residual } \text{SiO}_2) - (\text{residual } (\text{Mg}, \text{Fe})\text{O})$$

$$\text{ol} = (\text{residual } (\text{Mg}, \text{Fe})\text{O}) - (\text{residual } \text{SiO}_2)$$

where residuals mean the amounts remaining before making hypersthene.

(c) Even after using all of  $(\text{Mg}, \text{Fe})\text{O}$  for making olivine, sometimes, lack of  $\text{SiO}_2$  occurs (hy is less than zero in the above equation). In this case, we must make perovskite ( $\text{CaO} \cdot \text{TiO}_2$ ), if titanite was calculated in (a) of 3).

(d) If  $\text{SiO}_2$  is insufficient yet, we make nepheline ( $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) together with new amount of albite, after canceling old amount of albite, as follows.

$$ab = ((\text{residual SiO}_2) - 2(\text{residual Na}_2\text{O})) / 4$$

$$be = (\text{residual Na}_2\text{O}) - ab$$

(e) If  $\text{SiO}_2$  is furthermore lacked, we make leucite ( $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$ ), after canceling old amount of orthoclase. The procedure is in very rare case.

$$or = ((\text{residual SiO}_2) - 4(\text{residual K}_2\text{O})) / 2$$

$$lc = (\text{residual K}_2\text{O}) - or$$

(f) In the case of extreme insufficient of  $\text{SiO}_2$ , di or wo will be canceled, and we obtain calcium orthosilicate and olivine.

Furhtermore, we will make kaliophilite after lc is canceled.

Table-2 Molecular weight of C.I.P.W. normative minerals

| Normative mineral      | Chemical formular   | Mol.wt.  | Abb. |
|------------------------|---|----------|------|
| Quartz                 | $\text{SiO}_2$  | 60.06    | Q    |
| Corundum               | $\text{Al}_2\text{O}_3$   | 101.94   | C    |
| Zircon                 | $\text{ZrO}_2 \cdot \text{SiO}_2$                                     | 183.28   | Z    |
| Orthoclase             | $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$  | 556.50   | or   |
| Albite                 | $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ | 524.29   | ab   |
| Anorthite              | $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$          | 278.14   | an   |
| Leucite                | $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$  | 436.38   | lc   |
| Nepheline              | $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ | 284.05   | ne   |
| Kaliophilite           | $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$  | 316.26   | kp.  |
| Thenardite             | $\text{Na}_2\text{O} \cdot \text{SO}_3$                               | 142.05   | th   |
| Halide                 | $\text{Na}_2\text{Cl}_2$  | 116.91   | hl   |
| Sodium carbonate       | $\text{Na}_2\text{O} \cdot \text{CO}_2$                               | 105.99   | nc   |
| Acmite                 | $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 4\text{SiO}_2$ | 461.91   | ac   |
| Sodium metasilicate    | $\text{Na}_2\text{O} \cdot \text{SiO}_2$                              | 122.05   | ns   |
| Potassium metasilicate | $\text{K}_2\text{O} \cdot \text{SiO}_2$                               | 154.26   | ks   |
| Diopside               | $\text{CaO} \cdot (\text{Mg}, \text{Fe})\text{O} \cdot 2\text{SiO}_2$ | -        | di   |
| Hypersthene            | $(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$                   | -        | hy   |
| Wollastonite           | $\text{CaO} \cdot \text{SiO}_2$                                       | 116.14   | wo   |
| Enstatite              | $\text{MgO} \cdot \text{SiO}_2$                                       | 100.38   | en   |
| Ferrosilite            | $\text{FeO} \cdot \text{SiO}_2$                                       | 131.90   | fs   |
| Olivine                | $2(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$                  | -        | ol   |
| Forsterite             | $2\text{MgO} \cdot \text{SiO}_2$                                      | 140.70   | fo   |
| Fayalite               | $2\text{FeO} \cdot \text{SiO}_2$                                      | 203.74   | fa   |
| Calcium orthosilicate  | $2\text{CaO} \cdot \text{SiO}_2$                                      | 172.22   | cs   |
| Magnetite              | $\text{FeO} \cdot \text{Fe}_2\text{O}_3$                              | 231.52   | mt   |
| Chromite               | $\text{FeO} \cdot \text{Cr}_2\text{O}_3$                              | 223.86   | cm   |
| Hematite               | $\text{Fe}_2\text{O}_3$   | 159.68   | hm   |
| Ilmenite               | $\text{FeO} \cdot \text{TiO}_2$                                       | 151.74   | il   |
| Titanite               | $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$                    | 196.04   | tn   |
| Perovskite             | $\text{CaO} \cdot \text{TiO}_2$                                       | 135.98   | pf   |
| Rutile                 | $\text{TiO}_2$  | 79.90    | ru   |
| Apatite                | $3(3\text{CaO} \cdot \text{P}_2\text{O}_5) \cdot \text{CaF}_2$        | 3×336.31 | ap   |
| Fluorite               | $\text{CaF}_2$  | 78.08    | fl   |
| Calcite                | $\text{CaO} \cdot \text{CO}_2$  | 100.09   | cc   |
| Pyrite                 | $\text{FeS}_2$  | 119.96   | pr   |



## 5) Calculation of weight per cents of the minerals

Now, we obtain the molecular amount of normative minerals. Normally the amounts are recalculated in weight proportion. We multiply the molecular amount of each mineral by the molecular weight listed in Table-2. In this calculation, H<sub>2</sub>O was omitted. The total weight of such normative minerals and H<sub>2</sub>O is generally a little smaller than, but very close to, the total weight of oxides in original analysis. If we obtain the total weights of normative minerals, which are extremely different from the original total weight, the calculation may be wrong. We should also show the proportions of wo, en, fs, fo and fa in diopside, hypersthene and olivine.

### References

- Cross, W., Iddings, J.P., Pirsson, L.Y. and Washington, H.S. (1902), A quantitative chemico-mineralogical classification and nomenclature of igneous rocks. J. Geol., 10, 555-690.
- Washington, H.G. (1917), Chemical analyses of igneous rocks. U.S. geol. Surv. Prof. Pap., 99.

## Wet-chemical analysis of silicate minerals and rocks

Tadato Mizota

Wet-chemical analysis is valuable as a fundamental technique of chemical analyses. This method allows us to learn the basic treatments and principles of the analysis. Especially, this is suitable to understand methods of chemical treatment of a sample and preparation of standard solutions from reagents. These are necessary to handle modern equipments for chemical analysis. Wet-analysis including gravimetry is the most precise method for all analyses of main constituents in a sample. The process of decomposition of the sample is so important for chemical analysis in the fields of mineralogy, petrology and economic geology that it has been learned through the course of silicate analysis in this lecture. The lecture treated the method of analysis on the following elements: Si, Ti, Al, Fe<sup>3+</sup>, Fe<sup>2+</sup>, Mn, Ca, Mg, Na, K, P, and H<sub>2</sub>O content. The contents are as follows:

1. Introductory, significance of wet-chemical analysis
2. Sample preparation, rocks and minerals
3. Outline of the analysis, Main flowsheet and partial analysis
4. Details for main flowsheet, Determination of each element
5. Partial analysis
6. Standard solutions and calculation method for the analysis
7. Flame-photometry and atomic absorption spectrophotometry
8. Spectrophotometry (colorimetry)

Exercise: Units for chemical analysis

The X-ray fluorescence analysis was lectured partially.

The flowsheet of the analysis is described in detail in the part II of the volume in reference to analyses of granodiorite porphyry and K-feldspar performed in the training course of wet-chemical analysis.

## X-ray powder diffraction analysis for minerals

Tadato Mizota

X-ray diffraction is utilized for identification of minerals by pattern fitting on diffraction chart, determination of precise cell dimensions of minerals, and measurement of diffraction intensities of X-ray from crystalline or sometimes amorphous materials. The method is now essential for those who are specialized in economic geology. In this lecture, special attention was paid to give understanding for diffraction geometry. Preceding to complete recognition or various application of X-ray to our field as a strong tool, we must understand the concepts of a reciprocal lattice and Ewald's reflection (diffraction) sphere. The early half of the lecture involved these and treated only X-ray powder diffraction with practical examples. It is important also to calculate unit cell dimensions and Bragg's d-values for data processing of X-ray diffraction experiment. For this purpose, we must use electric computer. The latter half of the course consisted of computer programming to calculate cell dimensions for all the crystal systems by the least squares method with h k l d-values obtained from X-ray powder diffraction experiment. PC-1500 computer was used with the BASIC language for the programming and calculation.

The contents of the lecture were given as follows.

1. Crystallographic preparation for X-ray diffraction
  1. X-ray - crystal interaction
  2. Reciprocal lattice
  3. Interplaner distances
  4. Unit cell dimensions, Least squares method by using many d-values
  5. Calculation of matrix

2. Computer programming (BASIC)
  1. To calculate area of a circle with radius R  
Computer language and grammar
  2. Calculation of d-values from given cell dimensions  
d-values of pyroxene  
Reciprocal lattice and  $d^*$  relation
3. Programming of unit cell dimensions by the least squares method
  1. Flowchart
  2. LSUC/IGE program list
  3. Weight
  4. M and delta matrix calculation with weight
4. Standard deviations
  1. Propagation of standard deviations by calculations

The program list is shown below with the method of use. In this program, the weight for each data is neglected for calculation. NEC PC-8801 microcomputer system were introduced into the institute, after the lectures were completed. The conversion of the program into other computer system is simple, if the program is written in BASIC.

PROGRAM LSUC/IGE

```

1:REM LEAST SQU
  ARS FOR UNIT C
  ELL
2:DIM B$(6)
3:CSIZE 1
4:DIM H(30),K(30
  ),L(30),D(30),
  DS(30),A(30,6)
  ,M(6,7),C(6),F
  $(6),E(6),X(6)
  ,S(6)
5:INPUT "SAMPLE?"
  ";SA$
6:LPRINT "SAMPLE
  ---":SA$
7:B$(1)="CUBIC":
  B$(2)="TETRAGO
  NAL":B$(3)="HE
  XAGONAL"
8:B$(4)="ORTHORH
  OMBIC":B$(5)="
  MONOCLINIC":B$
  (6)="TRICLINIC
  "
10:INPUT "CRYSTAL
  SYSTEM="";SY
12:INPUT "WAVE LE
  NGTH="";LE

14:INPUT "NUMBER
  OF DATA="";N
22:FOR I=1 TO N
24:INPUT "HKL-D?"
  ;H(I),K(I),L(I)
  ,D(I)
26:LPRINT I;"";H
  (I);K(I);L(I);
  D(I)
28:DS(I)=1/D(I)/D
  (I)
30:NEXT I
35:LPRINT ""

```

Initial data

Sample name

Crystal system

| <u>Crystal system</u> | <u>SY</u> |
|-----------------------|-----------|
| <u>cubic.</u>         | 1         |
| <u>tetra.</u>         | 2         |
| <u>hexa.</u>          | 3         |
| <u>ortho.</u>         | 4         |
| <u>mono.</u>          | 5         |
| <u>tri-cl.</u>        | 6         |

Input

h k l d

list

A-matrix

```

40:IF SY>=2 THEN 6
  0
42:FOR I=1 TO N
44:A(I,1)=H(I)^2+
  K(I)^2+L(I)^2
46:NEXT I
48:R=1
50:GOTO 110
60:IF SY>=3 THEN 7
  0
62:FOR I=1 TO N
64:A(I,1)=H(I)^2+
  K(I)^2:A(I,2)=
  L(I)^2
66:NEXT I
67:R=2
68:GOTO 110
70:IF SY>=4 THEN 8
  0
71:FOR I=1 TO N
72:A(I,1)=H(I)^2+
  K(I)^2+K(I)*H(
  I)
74:A(I,2)=L(I)^2
75:NEXT I
76:R=2
78:GOT 110
80:FOR I=1 TO N
82:A(I,1)=H(I)^2.
  A(I,2)=K(I)^2.
  A(I,3)=L(I)^2.
84:NEXT I
85:R=3
88:IF SY=4 THEN 11
  0
90:FOR I=1 TO N
92:A(I,4)=2*H(I)*
  L(I)
94:NEXT I
96:R=4
98:IF SY=5 THEN 11
  0
100:FOR I=1 TO N
102:A(I,5)=2*H(I)*
  K(I):A(I,6)=2*
  K(I)*L(I)
106:NEXT I
108:R=6
110:LPRINT "CRYSTA
  L SYSTEM=";B$(
  SY)
115:LPRINT ""

```

Cubic

Tetragonal

Hexagonal

Orthorhombic

Monoclinic

Triclinic

M-matrix

```
120:FOR J1=1 TO R
122:FOR J2=1 TO R
124:MM=0
126:FOR I=1 TO N
128:MM=MM+A(I,J1)*
    A(I,J2)
130:NEXT I
132:M(J1,J2)=MM
134:NEXT J2
136:NEXT J1
```

A|-matrix

```
140:Q=R+1
142:FOR J1=1 TO R
144:MM=0
146:FOR I=1 TO N
148:MM=MM+A(I,J1)*
    DS(I)
150:NEXT I
152:M(J1,Q)=MM
154:NEXT J1
```

Sweep out method

```
155:IF SY=1 THEN 20
    2
160:S1=2:S2=1
162:FOR J1=S1 TO R
164:GOSUB 190
166:NEXT J1
168:S1=S1+1:S2=S2+
    1
170:IF S1=Q THEN 17
    4
172:GOTO 162
174:S1=R-1:S2=R
176:FOR J1=S1 TO 1
    STEP -1
178:GOSUB 190
180:NEXT J1
182:S1=S1-1:S2=S2-
    1
184:IF S1=0 THEN 20
    2
186:GOTO 176
```

```
190:REM "SUB190"
192:PP=M(J1,S2)/M(
    S2,S2)
194:FOR I=S2 TO Q
196:M(J1,I)=M(J1,I)
    )-M(S2,I)*PP
197:NEXT I
198:RETURN
```

Subroutine

X|-matrix

```
202:LPRINT "X(I)"
209:LPRINT ""
212:FOR I=4 TO R
214:X(I)=0
216:NEXT I
218:FOR I=1 TO R
220:X(I)=M(I,Q)/M(
    I,I)
221:LPRINT "X(";
    USING "###";I;
    ")=";USING "##
    #.#####";X(I)
222:NEXT I
225:LPRINT ""
```

Preparation to calculate  
unit cell constants

```
230:IF SY>=2 THEN 2
    36
232:X(2)=X(1):X(3)
    =X(1)
234:GOTO 250
236:IF SY>=3 THEN 2
    42
238:X(3)=X(2):X(2)
    =X(1)
240:GOTO 250
242:IF SY>=4 THEN 2
    45
244:X(6)=X(1)/2:X(
    3)=X(2):X(2)=X
    (1)
245:IF SY=4 THEN 25
    0
246:IF SY=6 THEN 24
    9
247:X(5)=X(4):X(4)
    =0
248:GOTO 250
249:Z1=X(4):Z2=X(5
    ):Z3=X(6):X(4)
    =Z3:X(5)=Z1:X(
    6)=Z2
```

Calculate reciprocal and direct cell dimensions

```

250:C(1)=SQR (X(1)   a*
   ):C(2)=SQR (X(   b*
   2)):C(3)=SQR (   e*
   x(3))
252:C(4)=X(4)/C(2)   cosa*
   /C(3):S(4)=SQR   sina*
   (1-C(4)^2)
254:C(5)=X(5)/C(1)   cosb*
   /C(3):S(5)=SQR   sina*
   (1-C(5)^2)
256:C(6)=X(6)/C(1)   cosy*
   /C(2):S(6)=SQR   sinY*
   (1-C(6)^2)
258:VS=C(1)*C(2)*C   v*
   (3)*SQR (1-C(4)
   )^2-C(5)^2-C(6)
   )^2+2*C(4)*C(5)
   )*C(6))
260:E(1)=C(2)*C(3)   a
   *S(4)/VS
262:E(2)=C(3)*C(1)   b
   *S(5)/VS
264:E(3)=C(1)*C(2)   e
   *S(6)/VS
266:E(4)=(C(5)*C(6)   cosa
   )-C(4))/S(5)/S
   (6)
268:E(5)=(C(6)*C(4)   cosb
   )-C(5))/S(6)/S
   (4)
270:E(6)=(C(4)*C(5)   cosy
   )-C(6))/S(4)/S
   (5)

```

Print out cell dimensions

```

272:F$(1)="A " :F
   $(2)="B " :F$(
   3)="C " :F$(
   4)="COSA":F$(5
   )="COSE":F$(6)
   ="COSG"
276:LPRING "UNIT C
   ELL DIMS REC
   IPROCAL CELL"
278:FOR I=1 TO 6
280:LPRINT F$(I);
   USING "###.##
   ###";E(I);C(I)
282:NEXT I
290:USING
302:LPRINT ""

```

Calculate d-values

```

305:LPRINT " H K
   L D(OBS) D(
   CALC)"
310:FOR I=1 TO N
320:TT=(H(I)*C(1)
   ^2+(K(I)*C(2)
   ^2+(L(I)*C(3)
   ^2+2*H(I)*K(I)
   *C(6)*C(1)*C(2)
   )
322:TT=TT+2*K(I)*L
   (I)*C(4)*C(2)*
   C(3)+2*L(I)*H(
   I)*C(5)*C(3)*C
   (1)
325:DS(I)=1/SQR (T
   T)
330:LPRINT USING " Print out
   ###";H(I);K(I) d(obs)
   ;L(I):USING "# d(calc)
   ##.###";D(I);
   DS(I)
340:NEXT I
345:CSIZE 2
350:END

```

Data Input

- 1) RUN
- 2) Sample Name
- 3) Crystal System (cubic 1, tetragonal 2, hexagonal 3, orthorhombic 4, monoclinic 5, triclinic 6)
- 4) Wave length in A
- 5) number of data (N)  N: less than 30
- 6) 

|                               |          |          |          |          |                                    |
|-------------------------------|----------|----------|----------|----------|------------------------------------|
| <u>h</u>                      | <u>k</u> | <u>l</u> | <u>d</u> | <u>h</u> | <input type="text" value="ENTER"/> |
| <input type="text" value=""/> |          |          |          | <u>k</u> | "                                  |
| <input type="text" value=""/> |          |          |          | <u>l</u> | "                                  |
| <input type="text" value=""/> |          |          |          | <u>d</u> | "                                  |



## Ore microscopy

Kenichiro Hayashi

An ore microscope is a kind of polarized microscope equipped with an incident illumination system to observe polished samples of ore under reflecting light. The basic system of ore microscope is composed of a rotating stage, objective lens, eyelenses, illumination source, reflector, polarizer and analyser. The sample should be provided through final polishing with diamond paste after several steps of preliminary grindings. In this lecture, method of the sample preparation, by using equipments installed in the Institute of Economic Geology, UMSA, has been described in detail. The fundamental optical properties were lectured such as color, reflectivity, reflection pleochroism which are observed under parallel nicols, and anisotropy and internal reflection under crossed nicoles. Furthermore, to the best identification of minerals, however, various techniques including examinations of polishing hardness, morphology, cleavage, twinning, etc. are necessary. Micro-hardness test and micro-reflectance measurement can be performed by means of ore microscope attached with corresponding accessories. Vickers hardness measurement and photo-spectrometry for reflectivity measurement have been described.

The texture of ore is important to discuss the origin of the deposit, because they reflect the formation conditions of minerals or deposit and successive changes which the ore suffered. Euhedral or subhedral morphology of minerals in orthomagmatic deposit, and zoning texture, colloform structure etc. observed in vein-type deposit are of the primary mineralization. Replacement, exsolution, deformation and metamorphic textures show secondary effects of postdepositional stage.

Fluid inclusions are often seen in minerals from hydrothermal origin. These are classified into primary, secondary and

pseudosecondary types in the stage of trapping, and liquid, gaseous, polyphase and CO<sub>2</sub>-bearing types in constituents observed under room temperature. The filling temperature which means homogenization temperature of two-phases in fluid inclusion at high temperature suggests that of formation. The theory and correction method of temperature have shown in terms of geothermometry.

The content of the lectures are listed below.

1. Introduction

Significance of ore microscopy for economic geology

2. Instrument

Mechanics and optical system: rotatable stage, lenses, illumination system, reflector, polarizer and analyser.

3. Sample preparation

Casting, grinding and polishing

4. Mineral identification

Optical properties: color, reflectivity, isotropism and anisotropism, internal reflection

Hardness and ore microscopy: polishing hardness, scratch hardness, micro-indentation hardness

Cleavage and parting

5. Quantitative measurement of reflectivity

Techniques: standard sample, background reflection, correction method

Application for determination of mineral composition and distinction of minute difference in structures

6. Hardness

Vickers hardness

7. Textures of ore minerals

Primary texture, secondary texture by replacement, secondary texture resulting from cooling

## 8. Fluid inclusion study

Nature and origin of fluid inclusion

Classification of fluid inclusions, gaseous, liquid, polyphase

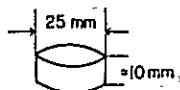
Mechanism of formation

Sample preparation and observation method

Fluid inclusion as geothermometer

P-V-T diagram of water and fluid inclusion

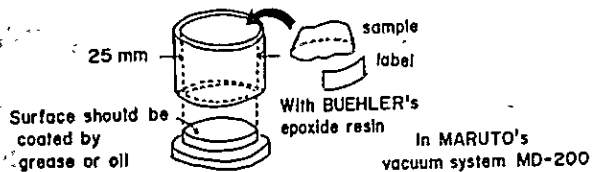
### SIZE & SHAPE



For STRUERS's automatic polisher DAP-2

Cylindrical shape

### COLD MOUNTING



### COMPRESSION MOLDING

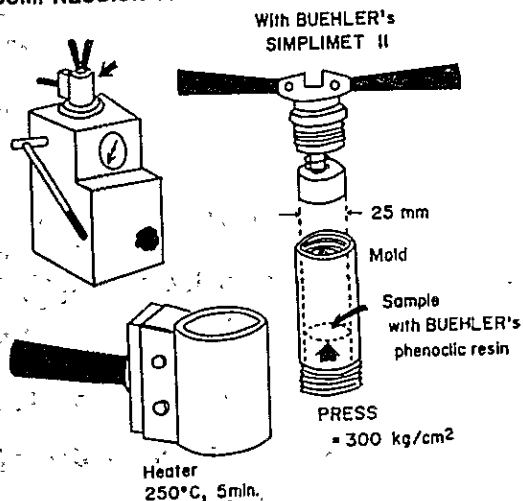
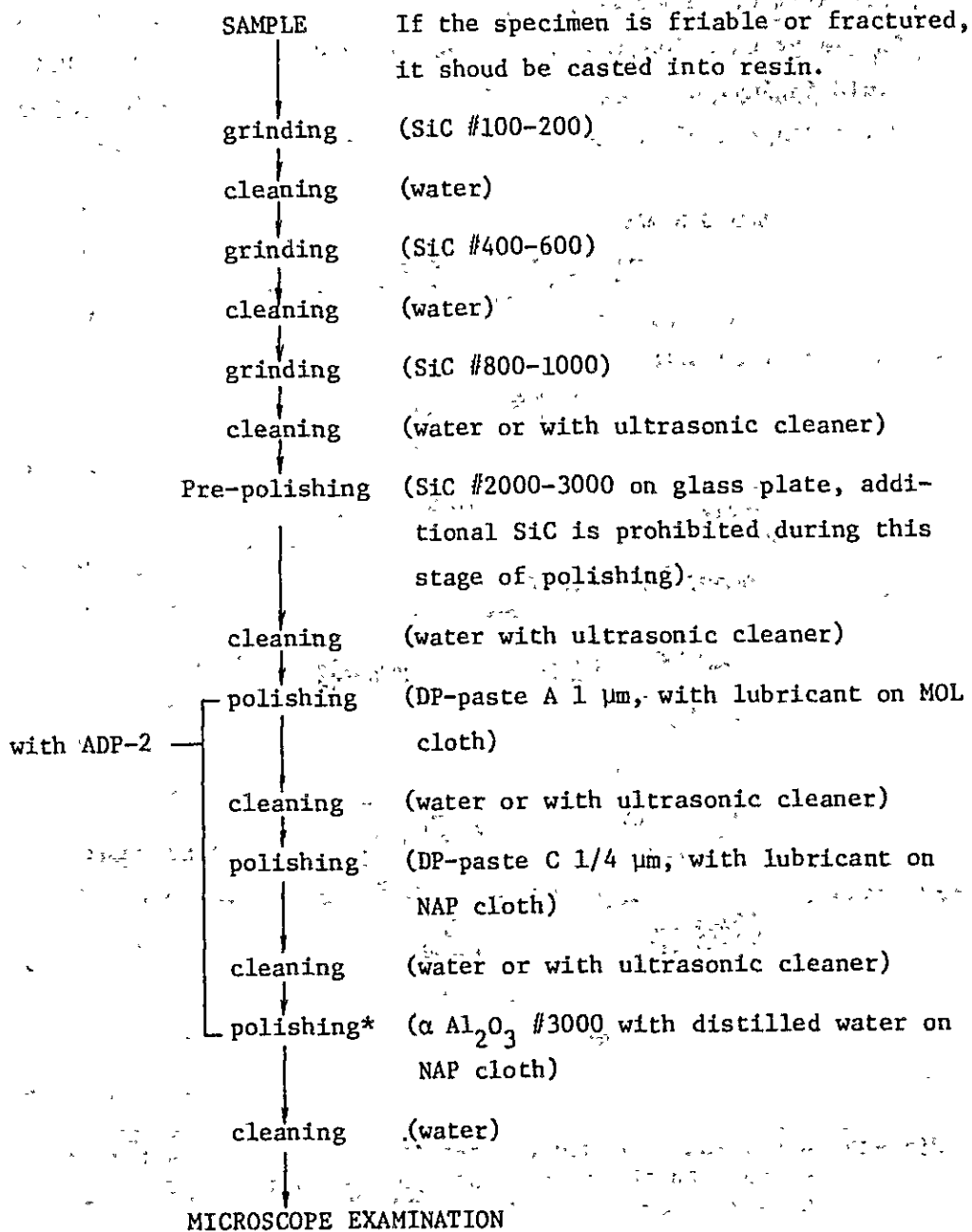


Fig.-24 Recommended method to prepare samples for ore microscope with the instruments in the Institute of Economic Geology at U.M.S.A.

The flowsheet of sample polishing for ore microscopy is shown below.



\* This step is not always necessary.

## Thermodynamics for Economic Geology

Shimpei Kano

The lecture has been carried out mainly on the basis of the textbook, "Thermodynamics", written by G.N. Lewis and M. Randall and revised by K.S. Pitzer and L. Brewer (1961), McGraw-Hill, New York.

Concepts in thermodynamics are important for investigators of economic geology to understand stability relations among minerals at definite conditions of formation in a deposit or to explain field observations and laboratory results on ore minerals. Modern economic geology includes also synthetic work of minerals to clarify relations among temperature and pressure of formation and chemical composition of the mineral. This enhances us also to become familiar with thermodynamics to explain the results or to plan the experimental works. The lecture consists of basic treatments in classical thermodynamics, as follows.

### I Definitions

The concept of "system": closed system, homogeneous system and heterogeneous system

Extensive and intensive properties

State functions

Equilibrium, process, and reaction

### II Molar properties

### III The first law of thermodynamics

Mechanical equivalent of heat

The law of conservation of energy

Internal energy

Pressure and temperature

Heat and work, Enthalpy

Heat capacity at constant volume or at constant temperature

Units of energy and correlated units

- IV Application of the first law to the perfect gas
  - Work and heat of isothermal and reversible expansion
  - Work of reversible and adiabatic expansion
  - The relation between  $C_p$  and  $C_v$
- V Heat capacities of pure substance and heats of reaction
  - Heat capacity values
  - Heat of reaction: Thermo-chemical reactions
  - Combination of equations
  - Standard state and heat of formation
  - Effect of temperature upon heat of reaction, relation between enthalpy and heat capacity, Kirchhoff's equation
- VI The Second law of thermodynamics
  - Entropy, the definition and nature
  - The law of dissipation of energy
  - Reversible and irreversible process
- VII Entropy and related equations as state function of thermodynamics
  - Entropy with volume and pressure changes
  - Helmholtz free energy
  - Gibbs' free energy
  - Spontaneous change
  - Clapeyron equation
- VIII Numerical calculation of Entropy
  - Entropy changes: fusion, vaporization, expansion and chemical reaction
  - Entropy change with temperature
  - Absolute value of entropy

IV The third law of thermodynamics

Practical formulation of absolute entropy

Standard entropy

X Free energy

Free energy of formation

Equilibrium and free energy

### 3.2.3 PRACTICA

El programa original presentado en diciembre del año 1982, estuvo orientado al análisis químico por vía húmeda y uso del microscopio. Las prácticas de análisis químico por vía húmeda, no pudieron ser realizadas sistemáticamente en razón del retraso de la llegada de los equipos donados.

#### .Microscopia y Petrografia

Hasta la llegada de los equipos donados, correspondientes al año fiscal de 1982, en Junio de 1983, fueron realizadas prácticas sobre uso del microscopio, utilizando para este fin un microscopio traído con anterioridad por los expertos.

A la recepción de equipos se efectuaron prácticas con los microscopios petrográficos, equipo fotográfico de microscopia, contador de puntos, platina y proyector universal.

Sin embargo este trabajo práctico de identificación de minerales por microscopia fué objetado.

A continuación se dara a conocer una síntesis del contenido de las prácticas individuales, participantes y tiempo de duración.

Del 1 al 15 de diciembre de 1982

- Observación microscópica sobre la mineralogía y alteración, en rocas alteradas de la mina San Jose de Oruro.
- Análisis microscópico sobre la formación de minerales en rocas eruptivas, en muestras de propiedad del Instituto de Geología Económica.

Responsable: Sr. G. Beccar

Del 17 de enero al 4 de febrero de 1983

- Estudio de la alteración de la roca e interpretación de la roca madre, en muestras eruptivas de las minas Quechisla y Colquechaca.



Del 14 al 18 de marzo de 1983

- Observación microscópica de la alteración y petrografía en muestras de roca alterada provenientes de la mina San Jose de Oruro.

Responsable: Sr. F. Saavedra

Del 4 al 30 de abril de 1983

- Estudio microscópico e identificación de minerales en muestras de granito del batolito Taquesi-Mururata

Responsable: Ing. A. Sanchez

Del 29 de junio al 29 de julio de 1983

- Instalación y ajuste de los microscopios petrográficos que llegaron.
- Entrenamiento sobre el ajuste y manejo de los mismos.

Responsables: Ing. A. Saavedra, Ing. A. Sanchez,  
Sr. G. Beccar, Sr. F. Saavedra

- Ajuste y manejo de la platina universal sobre rocas volcánicas de la mina San Jose. Explicación teórica de la óptica.

Responsables: Ing. A. Saavedra, Sr. G. Beccar

- Instalación del contador de puntos y explicación de su manejo. Prácticas sobre el cálculo de la composición mineralógica de rocas por conteo de puntos, utilizando muestras de rocas eruptivas de la mina San Jose de Oruro.

Responsables: Ing. A. Saavedra, Sr. G. Beccar

Del 29 al 31 de agosto de 1983

- Explicación y manejo del contador de puntos. Práctica sobre el cálculo de la composición mineralógica del granito de la zona Taquesi-Mururata.

Responsable: Ing. A. Sanchez

Del 1 al 6 de septiembre de 1983

- Observación microscópica sobre la greisenización del granito del Taquesi-Mururata y entrenamiento en la determinación de la composición química de sus plagioclasas.

Responsable: Ing. A. Sanchez

Del 3 al 7 de octubre

- Práctica sobre la identificación de minerales, determinación del nombre de la roca e interpretación, en rocas eruptivas.

Responsable: Sr. F. Saavedra.

Cabe hacer notar que este trabajo no pudo ser realizado sistemáticamente por falta de práctica en la identificación de minerales bajo el microscopio. Sin embargo se practico el ajuste y operacion del microscopio petrográfico, equipo fotografico de microscopia, contador de puntos y platina universal. Estos instrumentos son muy básicos y necesarios para la investigación en la petrografía.

Este entrenamiento fue necesario y util para la investigación de la contraparte y los resultados son incluidos en la segunda parte de este informe.

Experto responsable: Dr. Nakada

Análisis químico por via humeda

El trabajo de investigación en la geología económica incluye no solamente minerales de yacimientos, sino también rocas ígneas, metamórficas y sedimentarias, que son materiales componentes de la corteza terrestre.

Para practicar el análisis químico por via humeda se selecciono como material representativo de la corteza terrestre silicatos minerales y rocas ígneas a fin de aprender el manejo básico del análisis químico. Este método incluye el análisis de fusion de silicatos; usando el análisis volumétrico, análisis gravimétrico, espectrofotómetro y fotómetro de llama, siendo el area de su aplicación muy amplia para aprender el conocimiento y la técnica sobre análisis químico.

Dentro de este curso se han realizado las siguientes prácticas:

1.- Mantenimiento de la sala de análisis químico e instalación

- de equipos.
- 2.- Manejo de las balanzas de precisión.
  - 3.- Manejo del equipo para intercambio de iones y destilación de agua.
  - 4.- Práctica del espectrofotómetro.
  - 5.- Práctica en el equipo de absorción atómica y espectrofotómetro de llama.

1) Mantenimiento de la sala de análisis químico

Se dispusieron dos salas de análisis químico y un depósito para la instalación de equipos y la conservación de reactivos químicos. Este trabajo estuvo a cargo de los miembros de la contraparte boliviana y los expertos japoneses.

En las salas de análisis químico se instalaron los siguientes equipos principales:

- Draft chamber (YAMATO)
- Mesa principal de análisis (YAMATO)
- Espectrofotómetro de absorción atómica de llama (HITACHI)
- Espectrofotómetro (HITACHI)
- Destilador de agua con intercambiador de iones (YAMATO)
- Horno de mufla (YAMATO)
- Mesa de titulación, mesa lateral, estante de reactivos, etc.

2) Uso de la balanza química de precisión

Los días 3 y 4 de agosto, después de concluida su instalación, se practicó en el uso y manejo de estas balanzas. Las balanzas son dos, del tipo SAUTER y lectura directa; ambas tienen sensibilidad de 0.1 mg.

3) Destilador de agua con intercambiador de iones

El 4 de agosto se realizó la explicación del proceso de la regeneración de los iones y el manejo de grifos.

#### 4) Práctica de análisis químico por vía húmeda

El 19 de agosto, terminada completamente la instalación de instrumentos en la sala de análisis, seis miembros de la contraparte iniciaron experimentos de análisis químico. Las muestras utilizadas son del cuarzo porfírico de la cantera San Pedro, próxima a la mina San José de Oruro; y feldespatos potásicos del cerro Viscachani.

El I.G.E., que está situado en el campus de Cota Cota de La Paz, tiene una altura de 3.300 m.s.n.m.

El punto de ebullición del agua es de 85°C; razón por la cual se tenía duda en obtener los mismos resultados en los análisis que se obtienen al nivel del mar. Sin embargo fueron posibles los análisis, tan solo requiriendo mayor tiempo para la obtención de los precipitados. De igual manera el horno eléctrico no pudo alcanzar elevadas temperaturas con el quemador de gas L.P.G.

Los seis participantes analizaron la misma muestra de feldespato potásico y cuatro de los miembros la misma muestra de cuarzo porfírico. Para el análisis de Mn se utilizó el espectrofotómetro de absorción atómica y para el Na y K, el espectrofotómetro de llama.

Los resultados y métodos utilizados están en la segunda parte de este informe.

#### Difractómetro de rayos-X por el método de polvo

Este difractómetro fue entregado como parte de la donación el año 1981. Este equipo ayuda a dilucidar las características mineralógicas por identificación de diagramas de rayos-X difractados, medición de constantes de malla e intensidad de difracción de rayos-X. Para mantener y manejar a largo tiempo este equipo de alto grado de precisión, es necesario que la contraparte comprenda bien la teoría y el mantenimiento adecuado.

Debe ajustarse este difractor puesto que el poder de resolución tiene un alcance de  $\pm 0.01^\circ$  en el ángulo. El 7 de agosto de 1983 se practicó el ajuste del cero.

#### Análisis de diferencia y masa térmica

Se usa este aparato para dilucidar la característica de los minerales bajo condiciones de alta temperatura. Antes del traslado del Instituto se hicieron prácticas y orientó en el manejo y preservación del equipo.

#### Análisis de datos por sistema de micro-computador.

##### PC-8801 (NEC)

Antes de la llegada del computador PC-8801, en el curso de difracción de rayos-X por el método de PC-1500, se enseñó a calcular la constante de red y distancia interplanar. Utilizando el computador PC-1500 se practicó a confeccionar el programa de cálculo de la constante de la red cristalina por el método de los mínimos cuadrados. Asimismo se tradujo al inglés el texto del lenguaje BASIC para el sistema PC-8801 y PC-1500, distribuyéndose este texto a los miembros de la contraparte.

Experto responsable: Dr. Mizota

#### Microscopía de Opacos

La composición de la mena mineral, la relación de paragénesis entre minerales, el orden de cristalización de los minerales y la formación de la textura de la mena son muy importantes para considerar el origen del mineral. Esta observación únicamente puede efectuarse con el microscopio. También es necesario conocer que parte de la mena se está analizando; sin el uso de este método de análisis no podemos conocer que significado tiene el resultado del análisis.

La microscopía de opacos es básica para identificar minerales, por lo que para los miembros del Instituto de Geología Económica es necesario conocer bien las características minerales.

La microscopía de opacos consiste en la observación por reflexión con el microscopio polarizador. Se hizo la orientación con microscopios XTP y YBP de NIHON-KOGAKU a cargo del Dr. Hayashi. En las lecciones de microscopía de opacos se hizo una orientación sistemática.

La práctica esta programada para marzo de 1984, por lo que la orientación práctica se la realizo a nivel individual.

El Sr. Freddy Saavedra actualmente esta investigando la veta "J" de la mina San Jose y tiene una regular capacidad de manejo del microscopio de opacos.

Originalmente para la observación con el microscopio es necesario tener bastante experiencia. Los programas de estudio de la Universidad (Dpto. Geociencias) no consideran esta práctica, por lo que en este corto tiempo es difícil anumentar la capacidad de observación en los minerales. Por otra parte los minerales de la mina San Jose contienen varias sulfosales que tienen características similares bajo el microscopio; (ver grafico 1) siendo difícil su identificación y necesario un mayor conocimiento para poder diferenciar estos minerales, razon por lo que se estan preparando muestras para su práctica.

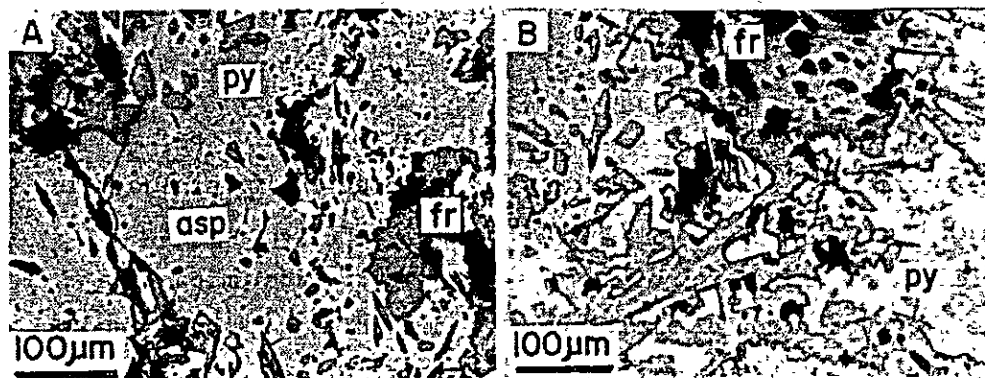


Grafico-1. Fotografías microscópicas de minerales de la veta "J" de la mina San José. Nivel - 380  
py: pirita. asp: arsenopirita. Fr: frankeita

Preparación de muestras para su observación con microscopio. Antes de observar la roca y el mineral bajo el microscopio es necesario preparar las muestras. En el caso de rocas es necesario pulir una cara y pegar al vidrio, para luego seguir puliendo hasta que pase la luz. Esta muestra es para la observación al microscopio de polarización de luz transmisible (microscopio de petrografía).

En el caso de minerales opacos en los que no atraviesa la luz (principalmente minerales metálicos), después del pulido de una cara, esta debe reflejar la luz, para luego observar con el microscopio de polarización y reflexión.

Para un estudio geológico es importante la observación microscópica de muestras, por esta razón la técnica de preparación de las mismas es fundamental e importante.

Dentro de los equipos donados el año 1982 están incluidos varios equipos y materiales de insumo para preparar muestras. Los equipos principales son: Pulidor de roca, Pulidor plano, prepulidor, etc. (gráfico-2); así como el disco caliente, equipo de impregnación de resina en el vacío, lavador ultrasónico, etc. Estos equipos fueron utilizados para las prácticas.

El encargado de la práctica, de la microscopía petrográfica es el Dr. Nakada; para la microscopía de opacos, el Dr. Hayashi. Estos cursos prácticos de tipo individual no tuvieron parte teórica.

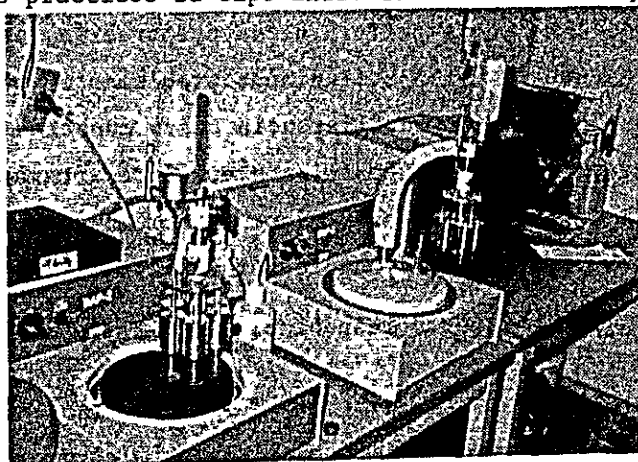


Gráfico-2 Vista del trabajo de pulir una muestra por uso del pulidor DAP-2.

El personal participante fue el siguiente: Orlando Sanjines, Alberto Sanchez, Gary Beccar, Freddy Saavedra. Por falta de un empleado técnico en preparación de muestras, el Sr. Juan Castillo chofer del Instituto ayudo en la preparación de las muestras. El tiempo total de las prácticas de preparación de muestras fue de 30 horas.

Cuando se prepara muestras pulidas es necesario modificar la forma de preparación de acuerdo a las características del material o tipo de equipo, no existiendo un método definido, por lo que cada persona tiene que buscar la mejor manera. Algunos métodos recomendables han sido dados durante las lecciones de microscopia de opacos. Los miembros de la contraparte estan preparando las muestras conforme a los métodos enseñados.

Para minerales blandos (carácter observado en sulfosales de minerales bolivianos) es necesario fijar varias veces la superficie con resina, pero la capacidad de la contraparte no ha llegado a este nivel todavia.

En el trabajo de preparación de muestras, para la observación microscópica, se necesita ensuciarse las manos aspecto este, que no agrada a algunos miembros de la contraparte, al parecer no les gusta este tipo de trabajo y no trabajan positivamente.

El Departamento de Geociencias de la Facultad de Ciencias Puras y Naturales tiene un empleado de preparación de muestras, y muy facilmente se puede pedir a el su preparación, pero no tiene buena calidad en su trabajo, teniendo problemas en el pulido final, observandose claramente la diferencia entre muestras preparadas en el Instituto de Geología Económica y en el Departamento de Geociencias, por lo que es recomendable que los miembros de la contraparte preparen sus muestras con sus propias manos.

Experto responsable: Dr. Hayashi

#### Inclusiones fluidas

Los minerales de yacimientos hidrotermales muestran frecuentemente inclusiones fluidas primarias, que han sido incluidas durante



el tiempo de cristalización. Después de la cristalización se forman otro tipo de inclusiones denominadas inclusiones secundarias.

Las inclusiones fluidas primarias se separan en dos fases; líquidas y gaseosas (inclusiones de dos fases) de acuerdo al enfriamiento gradual hasta su punto crítico. Fuera de las anteriores a veces se puede observar cristales de NaCl (inclusión de multi-fases) o inclusión de CO<sub>2</sub>.

En el caso de inclusiones de dos fases por calentamiento, se presenta finalmente solo una fase de inclusión fluida (líquido o gas) a cierta temperatura. Por la medida de esta temperatura y la corrección de la presión podemos suponer la temperatura de formación del mineral que contiene estas inclusiones. Este es el principio del geotermómetro por inclusión fluida.

Los fluidos que dieron origen a los minerales contienen NaCl en diferentes concentraciones; por el enfriamiento de las inclusiones fluidas se puede medir el punto de congelación y con esto podemos suponer la concentración de sales en la inclusión fluida.

Los dos puntos anteriormente citados son importantes para realizar la investigación de inclusiones fluidas. La práctica fue efectuada usando el microscopio de calentamiento y enfriamiento. Los encargados fueron los Dres. Nambu y Hayashi.

Actualmente la persona encargada de investigar las inclusiones fluidas es el Ing. Hernan Villena, quien realizó medidas de la temperatura de formación de inclusiones, en muestras de la mina San Jose bajo la dirección de los expertos Dres. Nambu y Hayashi.

Para medir las temperaturas es necesario conocer el error de medición. A tal efecto el Dr. Hayashi hizo la corrección de temperatura del tablero de calentamiento. Este método de corrección consiste en medir las temperaturas de fusión de los metales In, Sn, Pb y permanganato de potasio. El resultado muestra una temperatura mas alta que la determinada. Por ejemplo una temperatura medida de 400°C mostro un valor de 50°C mas alto. Este

error depende de la estructura del tablero de calentamiento, y puede explicarse por el efecto de convección del aire. Mas adelante pensamos mejorar el tablero de calentamiento con el Ing. Villena.

Si no se hace la corrección de la presión de formación, no se puede suponer la temperatura de formación de los minerales. Este es un punto en el que se debe pensar al corregir la temperatura. Actualmente tenemos resultados en los que no es necesario la corrección de la presión en vetas de la mina San Jose, debido a que este yacimiento es de origen supergénico.

Hasta el presente no se han hecho experimentos de enfriamiento.

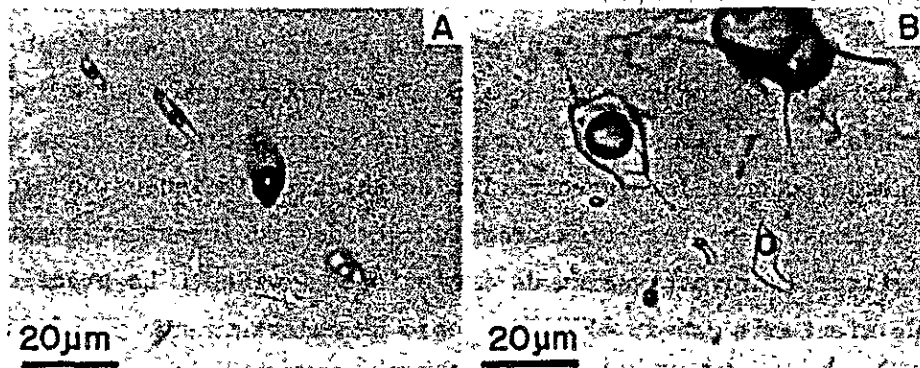


Gráfico-3 Inclusiones fluidas en cuarzo de la veta "J" en la mina San José. A y B corresponden al nivel - 380. Típica inclusión fluida formada por dos fases: una fase líquida y otra fase gaseosa. (encargado: Dr. Hayashi)

#### Técnica de fotografía.

Cuando se publica resultados de investigación la impresión es muy buena para el interlector si se observan fotografías que enseñan gráficamente lo propuesto. En el caso de un estudio geológico, las fotografías son tan importantes como el contenido literal. Asimismo cuando se hace una presentación oral de la investigación es importante utilizar diapositivos, de tal manera que la concurrencia comprenda mejor.

La técnica de fotografía en geología tiene tres puntos básicos: la primera técnica es el revelado y la impresión; la segunda es la toma de fotografías microscópicas; la tercera es hacer diapositivos.

Técnica de hacer diapositivos: Encargado Dr. Mizota;

Técnica de sacar fotografía microscópica: Encargado Dr. Hayashi.

Las personas que han recibido este entrenamiento son: el Ing. Orlando Sanjinés, Ing. Alberto Sánchez, Ing. Hernán Villena, Sr. Gary Beccar, Sr. Freddy Saavedra.

Los equipos usados fueron, cámaras, elementos de sala oscura, y aparato de tomar fotografías microscópicas.

Se deben seleccionar y utilizar papeles sensibles, materiales y reactivos de acuerdo a los objetivos respectivos; esto es, lo que en principio se orientó a los miembros del I.G.E. Ellos ahora pueden hacer revelado e impresión, pero no llegan a comprender suficientemente la combinación entre papeles y reactivos.

En caso de sacar fotografías con microscopio, la fuente luminosa normalmente es una lámpara de tungsteno con, o sin halogeno; y debiera considerarse la combinación de la fuente y el film. En la fotografía blanco y negro el filtro no tiene importante influencia, sin embargo siempre es mejor usar filtro verde. En caso de fotografías de color la fuente luminosa es diferente que en el caso normal; por esta razón se debe usar filtro azul. Cuando se utiliza film para lámpara de tungsteno no hay problema, pero en Bolivia no se encuentra film para lámpara de tungsteno. El tiempo de exposición no tiene problema para la fotografía microscópica (NIHON KOGAKU: AFX-35), porque utiliza aparatos automáticos; pero bajo condiciones especiales, por ejemplo, para nicoles cruzados se debe hacer correcciones del tiempo de exposición. Este punto todavía no es de comprensión por los miembros del I.G.E.

(encargado: Dr. Hayashi)

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Foto-1 Ing. R. Santiviáñez, Director del Instituto de Geología Económica observando secciones delgadas con microscopio. de polarización.

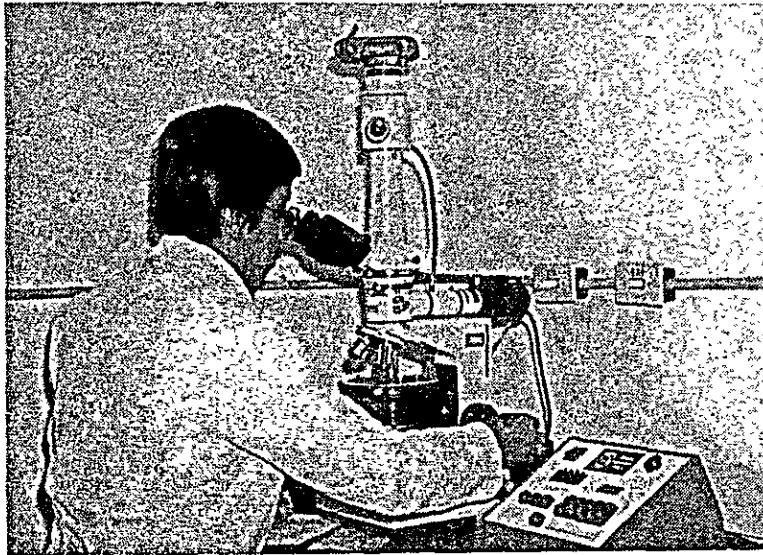


Foto-2 Ing. H. Villena usando el contador de puntos para análisis modal con microscopio.



Foto-3A Ing. O. Sanjinés terminando la separación de magnesio.



Foto-3B Ing. H. Villena filtrando.

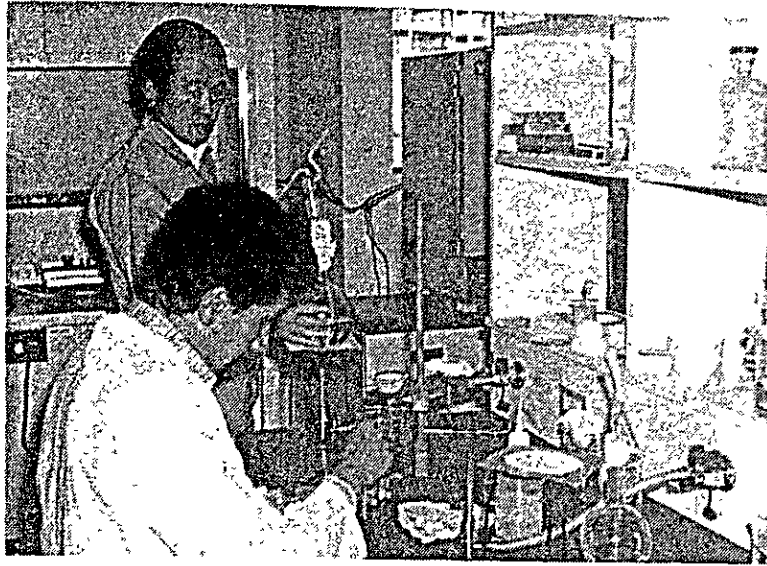


Foto-3C Ing. E. Soria lavando el precipitado junto al experto Dr. Mizota orientando el procedimiento.



Foto-3D Sr. F. Saavedra separando oxalato de calcio por filtración.



Foto-4 Ing. O. Sanjines practicando técnica fotográfica.

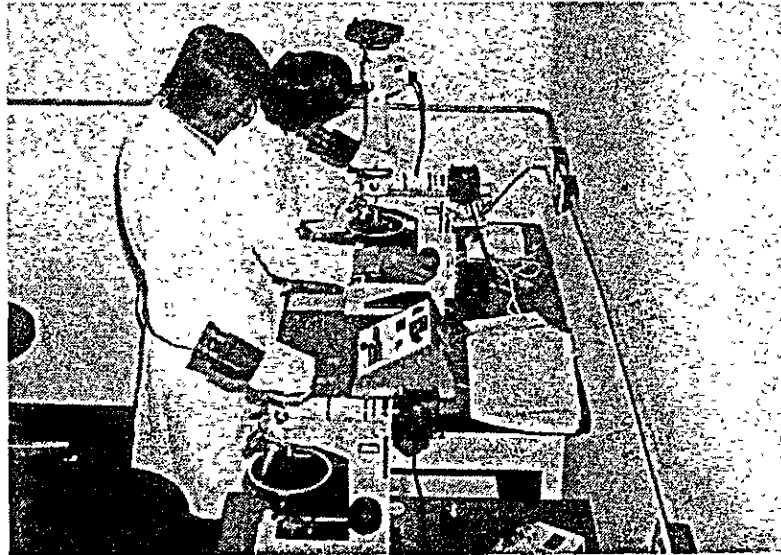


Foto-5 Ing. A. Saavedra e Ing. H. Villena practicando con el microscopio de opacos.



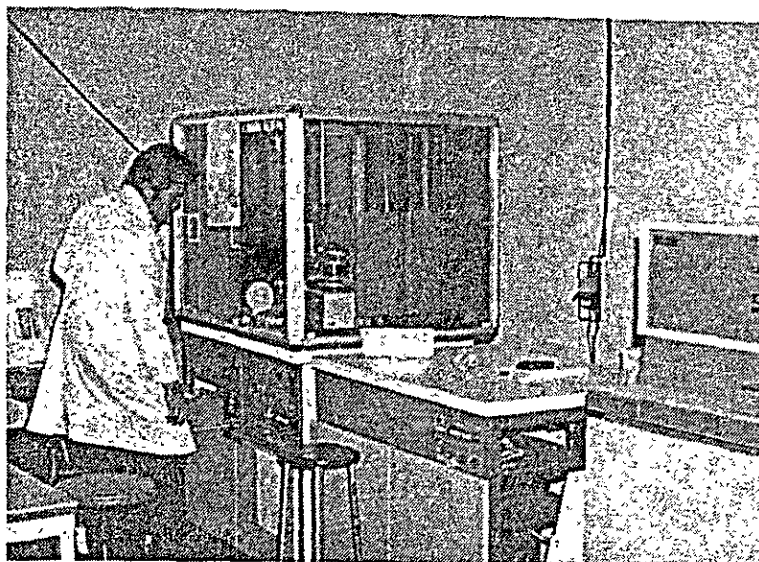


Foto-6 Experimento de difracción de rayos-X por polvo.



Foto-7 Práctica del manejo del microcomputador NEC-8801.

