Geology and Mineralogy of Granites

1. What is granite?

   Controversy surrounding the origin of plutons (granites)

2. Classification

   Modal classification, Alphabetical classification etc.

3. Granitoids series and mineralization

   Examples in Japan

4. Mineralogy of granites

   Hornblende barometer, Twinning of plagioclase

5. Granites in central Mongolia

   Bayankhongol project in 1995-1999.

1. What is Granite (in a broad sense)?

- Granite: A visibly crystalline plutonic rock with granular texture; composed of quartz and alkali feldspar with subordinate plagioclase and biotite and hornblende. (Dictionary of Geology & Mineralogy. McGRAW-HILL)
- Granite: A plutonic rock consisting essentially of quartz, alkali feldspar and plagioclase in variable amounts usually with hornblende and/or biotite. Now defined modally in QAPF field 3. (A Classification of Igneous Rocks and Glossary of Terms. Edited by R.W. Le Maitre, 1989, Blackwell Scientific Publications)
- Granitoids: It is now commonly used as synonym for a granitic rock, i.e., any plutonic rock consisting eseentially quartz, alkali felidspar and/or plagioclase. (ditto)

Neptunists vs. Plutonists

Origin of Granite in last half of 18th century

Neptunists believed that granites - along with all rocks – were precipitated from the oceans.

e.g., A.G. Werner (1749-1817)

Plutonists posited that plutonic rocks had their origin in fire and were crystallized from magmas.

e.g., J. Hutton (1726-1797)

From Wikipedia

From Wikipedia

Johann Wolfgang Goethe

(1749-1832)

Neue Gesamtausgabe des Originalverkages.
Schriften zur Geologie und Mineralogie.

- Goethe was a very famous German poet, novelist, scientist, and politician. His works include “Faust” and “Die Leiden des Jungen Werthers”.
- He was familiar to geology and mineralogy, too. He was a Neptunist. He supported Werner. He believed Granite was precipitated from cloudy water.
- “Goethite” is named after Goethe.

Neptune and Pluto

Neptune in Roman Mythology
or Poseidon in a Greek Mythology
God of the sea and earthquakes

Pluto in a Roman Mythology
or Hades in a Greek Mythology
God of the underworld

From National Earth Science Teachers Association (NESTA)

Dikes

Ultimately, it was the recognition of dikes (tabular bodies of rock crosscut older rocks) that vanquished the Neptunists. Plutonists successfully argued that these rocks could not have been deposited from the sea.

Dike, Sor Rondane, Antarctica

Room problem

Volcanic rocks can be witnessed eruptions as a crystal-liquid mixture (clearly igneous). However the evolution of plutonic rocks is not directly observable.

Room problem:
When granites intrude as magmas, how are the wall rocks displaced in order to make space for the granite?

Granitization

Transformists vs. Magmatist

During a 1947 conference by GSA, the origin of plutons had evolved to debate between a melt-dominated mechanism (crystallization from a magma – magmatism) or a metasomatic mechanism with minor melt (the dominantly solid-state alteration – granitization).
The former idea is an insistence of the Magmatists, the latter idea is that of the Transformists.

Geological occurrences and experimental petrology support the concept of magmatism.

A revival of the room problem

A look into the room problem and plutonic-volcanic connections provides a good view into why it is critical to understand the pace of plutonism. During the late 1980s to early 1990s, there was a revival of interest in the room problem for granite plutons.

How can we consider intrusive mechanisms while thinking the room problem?

1. Stoping (Remarks; this not stopping)
2. Amalgamation of many dikes and/or sills

Magmatic stoping

↑

----Roof----

Shale

↓

↑

Granite

A process of igneous intrusion in which magma gradually works its way upward by breaking off and engulfing blocks of the country rocks.

Amalgamation of many dikes and/or sills

It is proposed that most granitic plutons could form through the amalgamation of many dikes and/or sill. The earliest intrusions would cool quickly and preserve contacts due to contrast between wall-rock and magma temperature. An incrementally assembled granite pluton spends significant intervals at or near magmatic temperatures, helping to erase contacts between increments.

Intrusive relation between two granitic bodies

Inada Granite
Coarse-grained granite

Amabiki Granodiorite
Leuco margin

Medium-grained granodiorite

Dating plutonic rocks (Granites)

Techniques for determining the age of plutonic rocks have focused in the past 20 years on the decay of uranium to lead (U-Pb chronology) and the decay of ^{40}K to ^{40}Ar (^{40}Ar- ^{39}Ar, or Ar-Ar chronology).

Zircon U-Pb age: Zircon begins to crystallize (zircon saturation temperature, >800℃) when the magma becomes completely solid.
Titanite U-Pb age: Titanite leaks daughter Pb down to temperature of 680℃ (closure temperature).
Hornblende Ar-Ar age: The closure temperature is 550℃.
Biotite Ar-Ar age: The closure temperature is 350℃.

Cooling rates

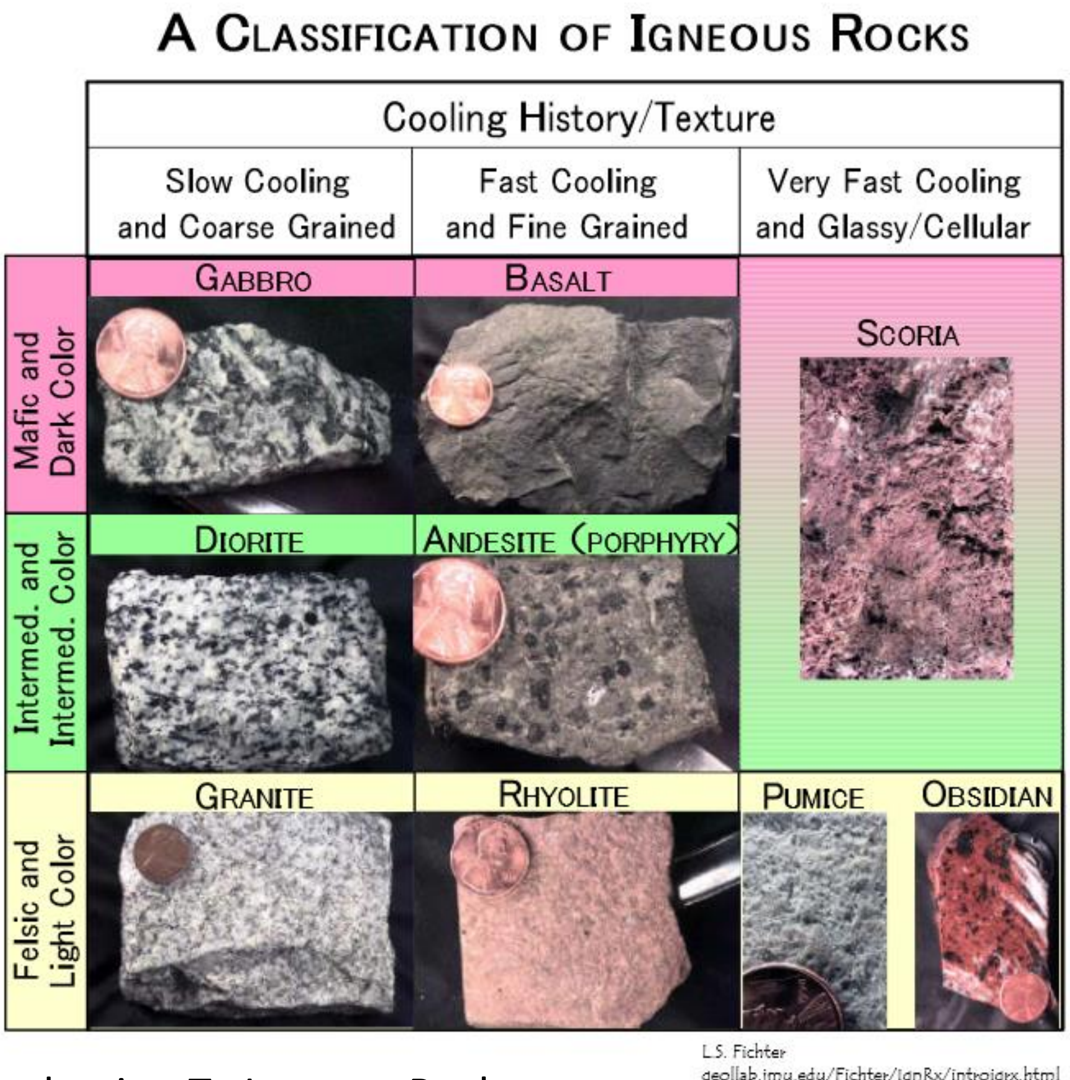
Incrementally assembled plutons slowly add heat to the system over the duration of pluton assembly. Individual pulses initially cool quickly. Therefore high-temperature chronometers may yield a tight age cluster and low-temperature chronometers may yield a spread in ages. In the Tuolumne Intrusive Suite, Sierra Nevada (CA, USA), the magmas had accumulated and solidified over a 10 My interval between 95 Ma and 85 Ma.

Sierra Nevada, CA

2. Classification

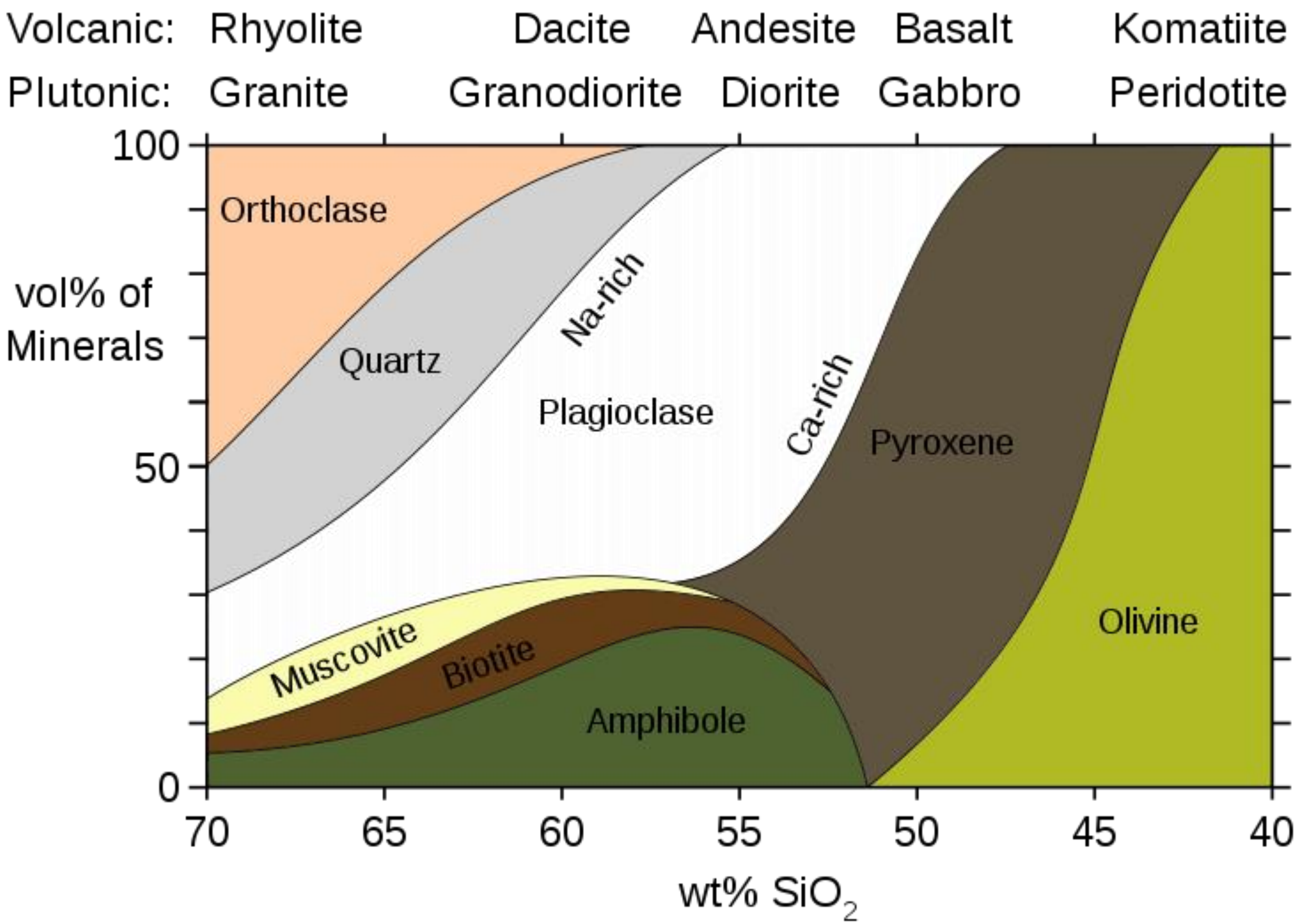
Basic and qualitative classification

Granite is felsic and light colored coarse-grained. Corresponding volcanic rock (fine-grained rock) is rhyolite.



An Introduction To Igneous Rocks
http://csmres.jmu.edu/geollab/Fichter/IgnRx/Introigrx.html

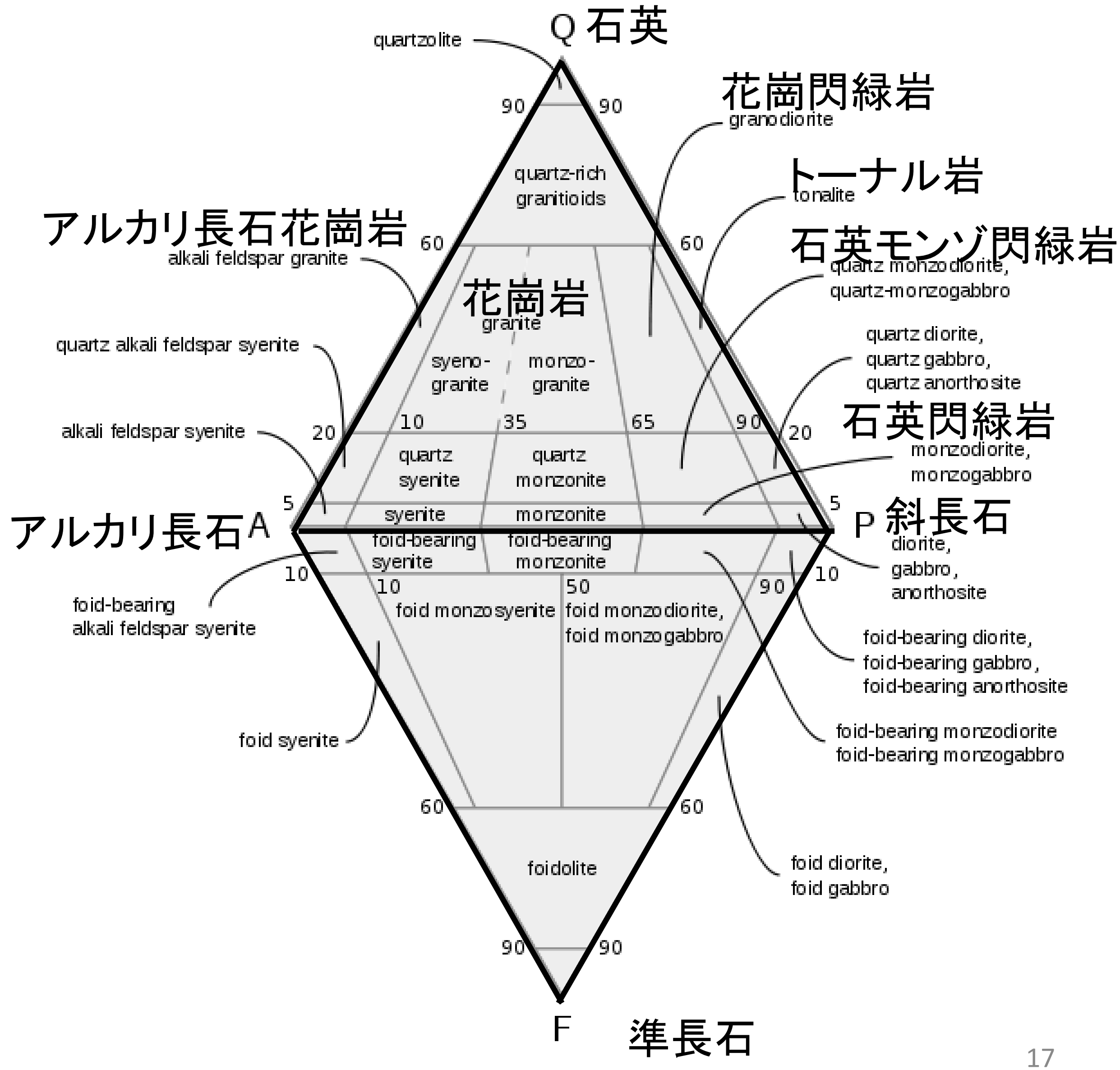
Classification of igneous rocks based on mineral assemblage



Modal classification of granitoids

Quantitative classification

Mineral volume is analyzed by point counter under microscope or image analyzer.



Alphabetical classification (I, S, M, A, -type)

I-type/S-type Proposed by Chappell & White

I-type Rich in Ca
Occurrence of Ca-bearing mafic minerals such as hornblende.

S-type Rich in K and Al and poor in Ca and Na
Presence of aluminous minerals such as cordierite, garnet, Al_2SiO_5 minerals and muscovite.

※ The I–types are contributed by the igneous rocks in their magma genesis and the S-types by the pelitic sedimentary rocks.

Alphabetical classification (I, S, M, A, -type)

M-type	Rich in Ca and poor in K.
	Related to mantle.
	---This type name is now not used.
A-type	High alkali and low H_2O (anhydrous) contents.
	---Name R-type is also used. R is after restite.

※ The M-type granitic magma is related with the low alkaline mafic igneous rocks of the upper mantle origin. The A-type granitoids are often accompanied by the felsic igneous rocks of the alkali rock-series.

3. Granitoid series

The greatest contribution to the granite petrology during the last quarter of 20th century would be the proposition of the granitoid series：magnetite−series, ilmenite−series and alphabetical classification of I-type, S-type, M −type and A-type.

The granitoid series has been employed as a tool for mineral exploration, because they are closely associated with particular metal deposits. Australian and Japanese geologists have played an important role on the establishment of the granitoid series.

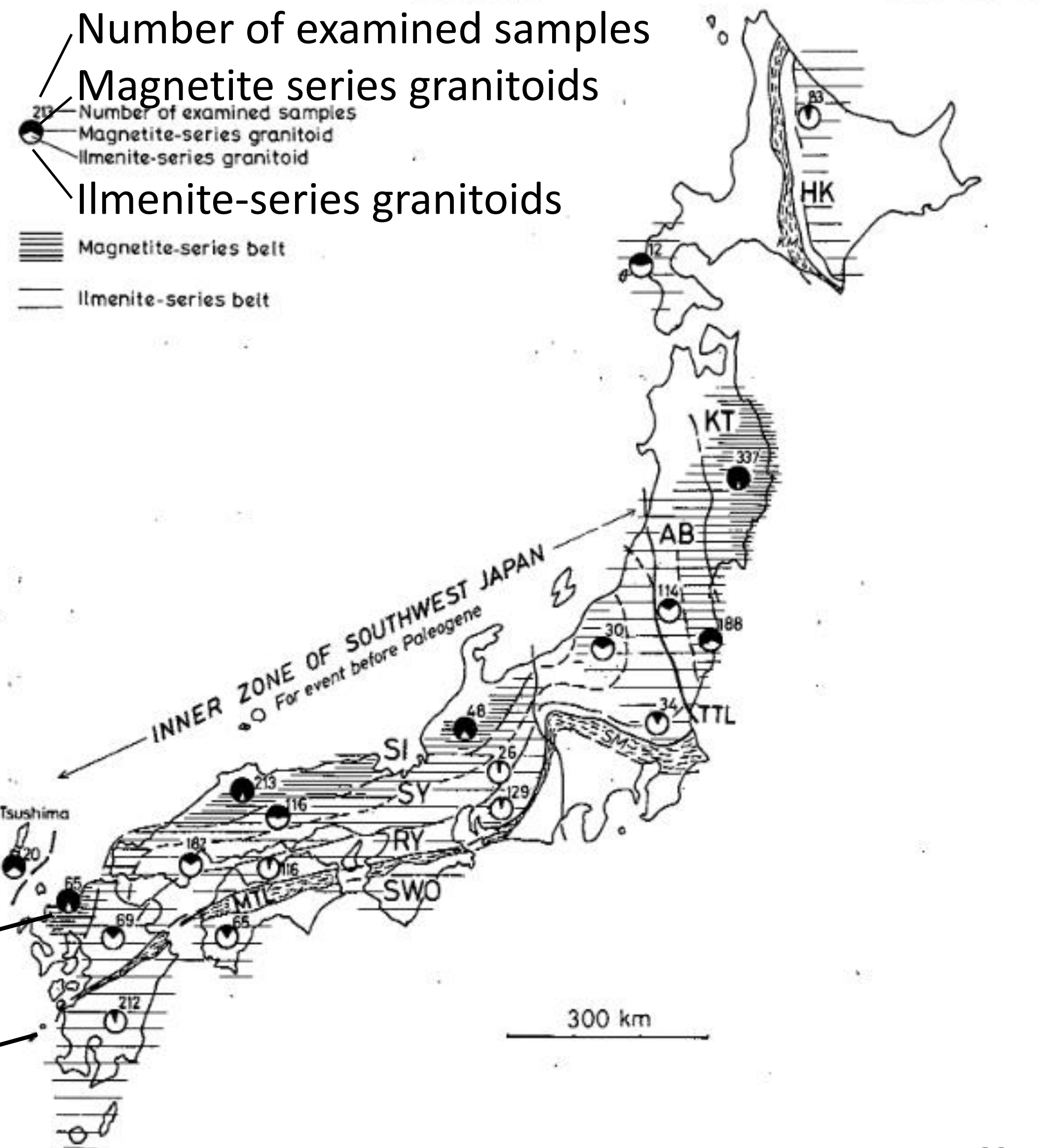
Granitoids series proposed by Ishihara

The magnetite−series granitoids are characterized by the presence of magnetite and high Fe^{3+}/Fe^{2+} whole −rock ratio and crystallize under the oxidized condition .
The ilmenite-series granitoids are characterized by the lack of magnetite and low Fe^{3+}/Fe^{2+} whole-rock ratio and solidify under the reduced environment .
The magnetite−series granitoids are closely related in their magma genesis to the igneous rocks oxidized on the earth's surface and the ilmenite-series granitoids the crustal materials containing crustal carbon.

Distribution on the granitoids series

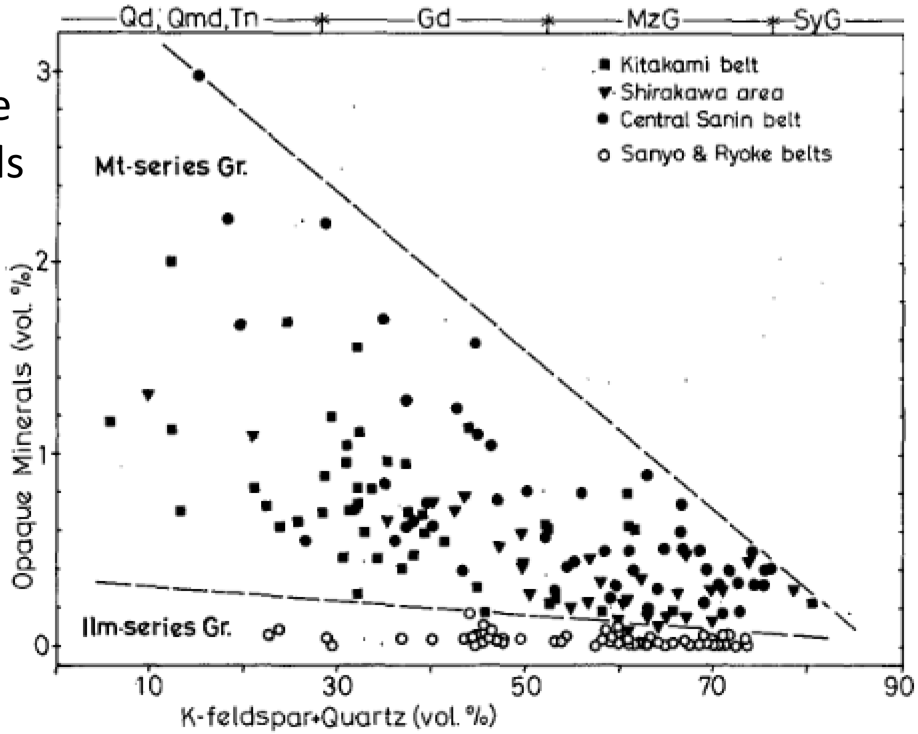
In Southwest Japan, the ilmenite series rocks are dominant in Ryoke and Sanyo belts and the magnetite series rocks are dominant in San-in belt.

(Ishihara, 1977)



Granitoids series based on modal analyses

Opaque minerals (vol. %)



K-feldspar + quartz (vol. %)

The granitoids series rocks are distinguished from modal analyses.

How to distinguish the granitoids series type in practical

1. Opaque mineral modal data: 0.1 vol.%
2. Magnetic susceptibility:100x10^{-6}emu/g, 1 or 3x10^{-3}SIU
3. Whole rock chemistry: Fe_2O_3/FeO (wt. %): 0.5

The magnetite series rocks show over these values; the ilmenite series rocks less than these values.

Small magnet is cheap tool to distinguish granitoids series.

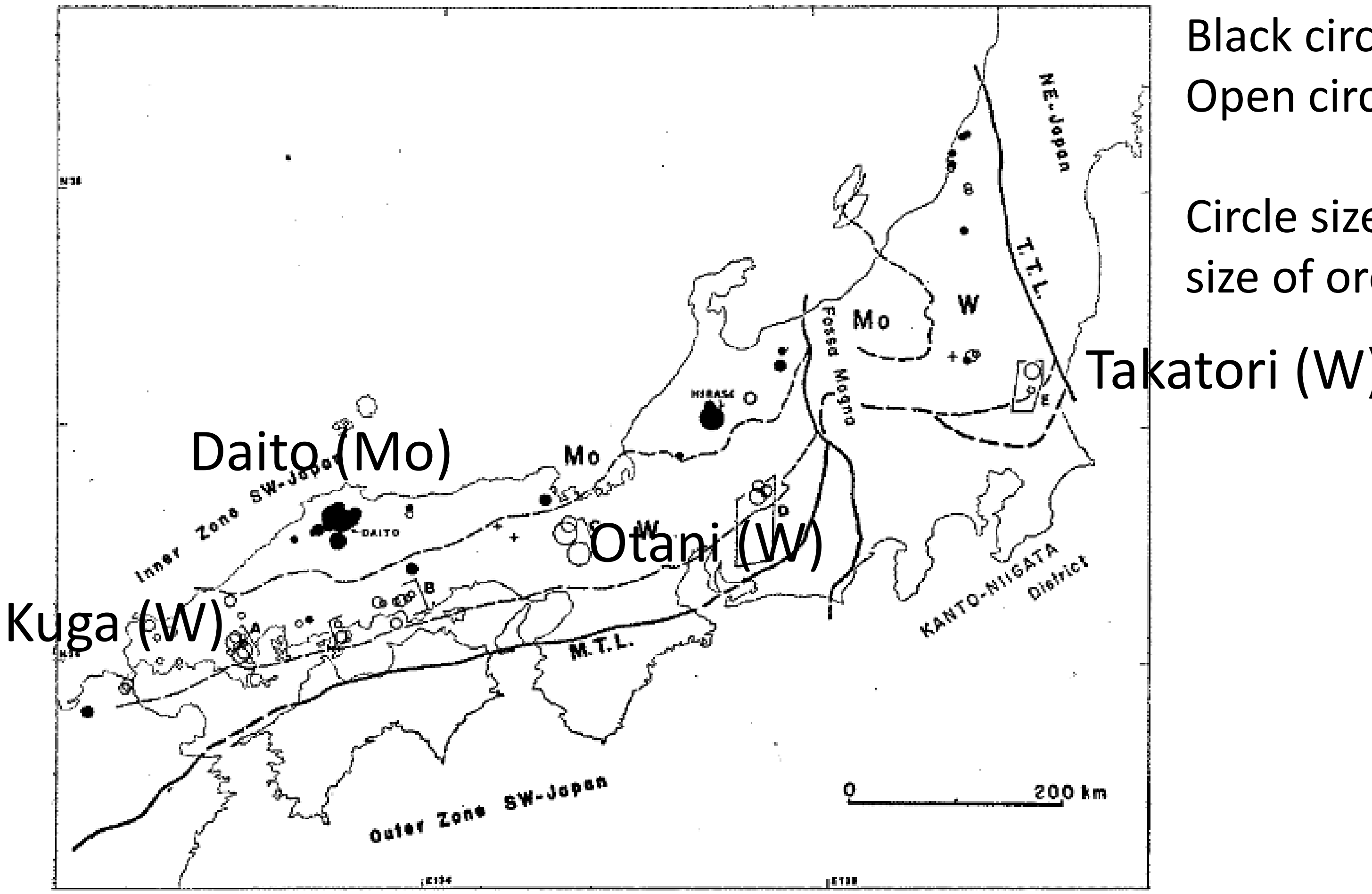
KT-10

Homepage of the Raax Co., Ltd

Granitoids series and metal deposits

Selected items	Cu-Mo deposits	Sn-W deposits
Related granitoids	Magnetite-series	Ilmenites-series
Rock composition	Tonalite-granite	Granite
Breccia pipe	Common	Rare-none
Pegmatite cap	None	Common
Orebody	Large vertical extent (1-3 km)	Small vertical extent (100-300 m)

Molybdenum and Tungsten ore deposits in south-west Japan



Black circle, Mo deposit
Open circle, W deposit

Circle size represents size of ore deposit.

第１図　西南日本内帯のモリブデン・タングステン鉱床の定量的表示(Ishihara, 1971 原図)。
●はモリブデン鉱床、○はタングステン鉱床、共に大きさは鉱床の規模を表す。
A は山口県東部、B は広島県東部-岡山県南部、C は京都府下、D は岐阜県苗木地域、E は茨城県高取近傍の鉱床群。

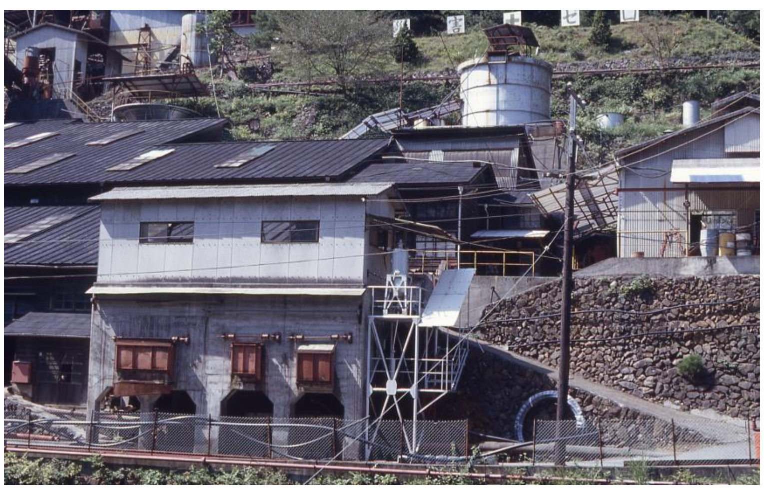
Kuga Mine (Tungsten)

This mine has long history, over 400 years.
1573-1591; Silver
1596-1614; Tin
1847-1853; Copper

Working and closing were repeated, then this mine worked for producing tungsten.
1993; Closed

This mine is now used as a amusement park.   We see some mining facilities.

Kuga Mine Park



Upper guide maps are cited from this mine park's website.

Left photo shows Mineral dressing facility at time of working. Photo by Takahashi, around 1983.

4. Mineralogy of granites

Part 1
Hornblende geobarometer

Total Al content（Al（t））of magmatic homblende coexisting with melt, hydrous fluid, biotite, quartz, K－feldspar, plagioclase （oligoclase to andesine）and two phases of sphene, magnetite or ilmenite in granitoids correlates linearly with crystallization pressure at the time of intrusion.

Phase rule; F=C+2-P

C=10 (SiO_2, TiO_2, --,H_2O); P=9 (hornblende, biotite, --, melt, vapor)

F=10+2-9=3, Solidus temperature=700℃, Composition of plagioclase=Oligoclase

Therefore, F=1, which means pressure is variable.

Why does Al become an indicator?

Simplified reaction is
2Quartz + 2Anorthite + Biotite = Hornblende + Orthoclase.
Within hornblende, (Mg, Fe)Si can replace Al Al.
As a result, Al content becomes an indicator of pressure at crystallization.

Hornblende geobarometry

Hammerstrom and Zen (1986)

P(±3kbar)=−3.92+5.03Al(t)

P; Pressure (kbar), Al(t); Total Al（O=23） in hornblende

Hollister et al. (1987)

Available in 2−8kbar

P(±1kbar)=−4.76+5.64Al(t)

Schmidt (1992)

Based experiment. Available in 2.5−13kbar

P(±0.6kbar)=−3.01+4.76Al(t)

These are the barometers in early stage of this type research (Takahashi, 1993). Recent works should be reviewed if necessary (e.g., Enami, 2013).

Pressure estimated from Al-in-hornblende (Takahashi, 1993)

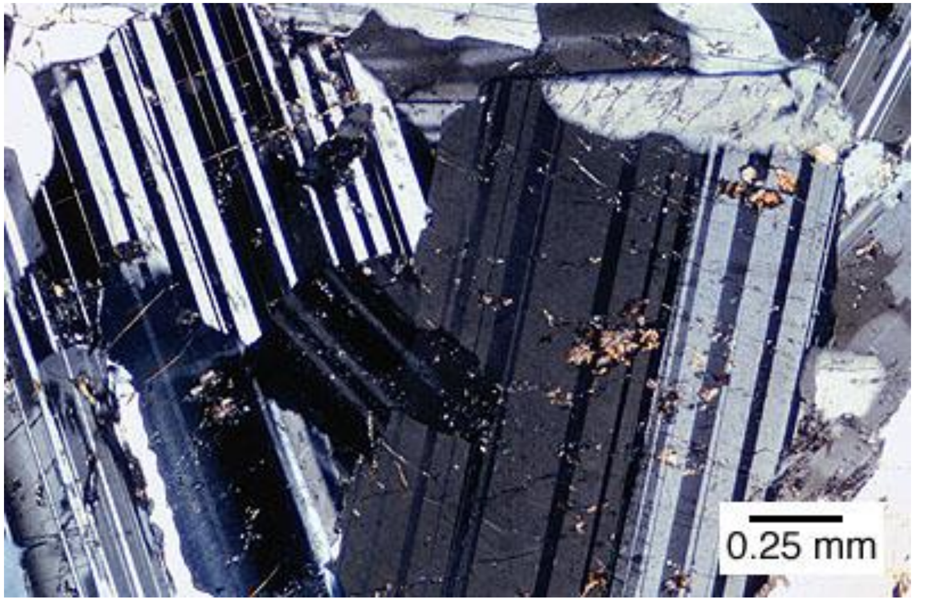
第２表　角閃石中の Al 総量から推定した中国地方の花崗岩類の圧力（kbar）

Table 2　Pressure (kbar) estimated from Al-in-hornblende in the granitoids of Chugoku District in Japan

Belt		Central Chugoku		Eastern Chugoku	
SAN-IN		Daito gd	<2	Ningyo-pass gr	<2, 3.2, 3.4
		Yokota gr	<2	Okutsu gd	2.2
SAN-YO	Stock			Small granitic bodies	2.9, 3.9, 4.2
	Batholith	Hiroshima gr	3.3, 3.4, 4.1	Mannari gr	3.6
RYOKE	Massive			Shiratori gr	4.0
	Gneissose	Takanawa gd	4.2	Shido gd	4.7, 5.0
				Shido gr	5.2, 6.4, 8.5

Numbers are pressure (kbar) estimated from chemical data of Tainosho et al. (1979), Czamanske et al. (1981) and Takahashi (1989), using geobarometer of Hollister et al. (1987) (2-8kbar) and Schmidt (1992) (8-13kbar). gd: granodiorite, gr: granite.

Mineralogy of granites, part 2
Plagioclase twinning



Gorai (1951)

Plagioclase twinning types are determined under microscope.

Type1---A-Twin
Type3---C-Twin
Type4---C-Twin
Type2---A or C-twin

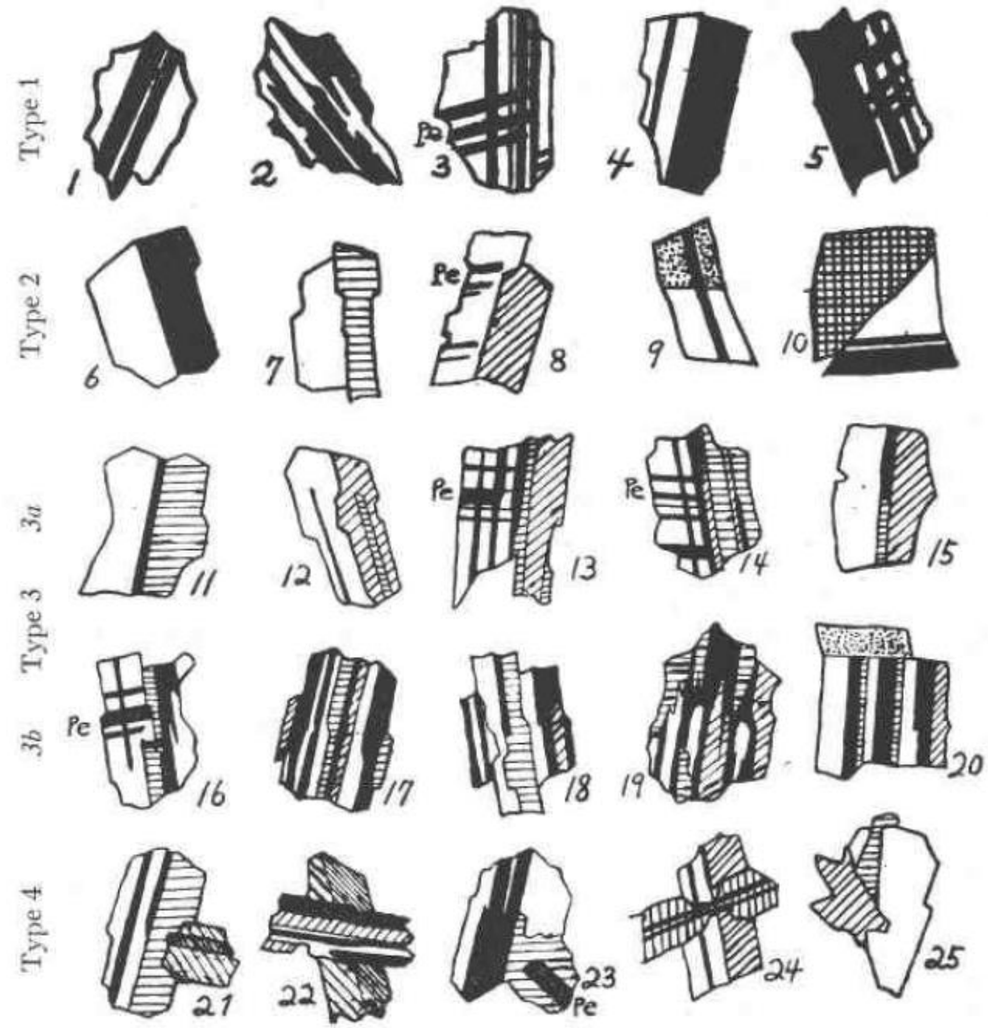


FIG. 1. Four types of twinned plagioclases.
Type 1. Polysynthetic twins and their modifications.
Type 2. Simple twins and their modifications.
Type 3. Complex twins and their modifications.
Type 4. Penetration twins.

Plagioclase of various granitic rocks (Gorai, 1951)

U: Untwined
A: A-twin
C: C-twin

This discrimination was used for granite debate, i.e., magmatism origin or metasomatism origin.

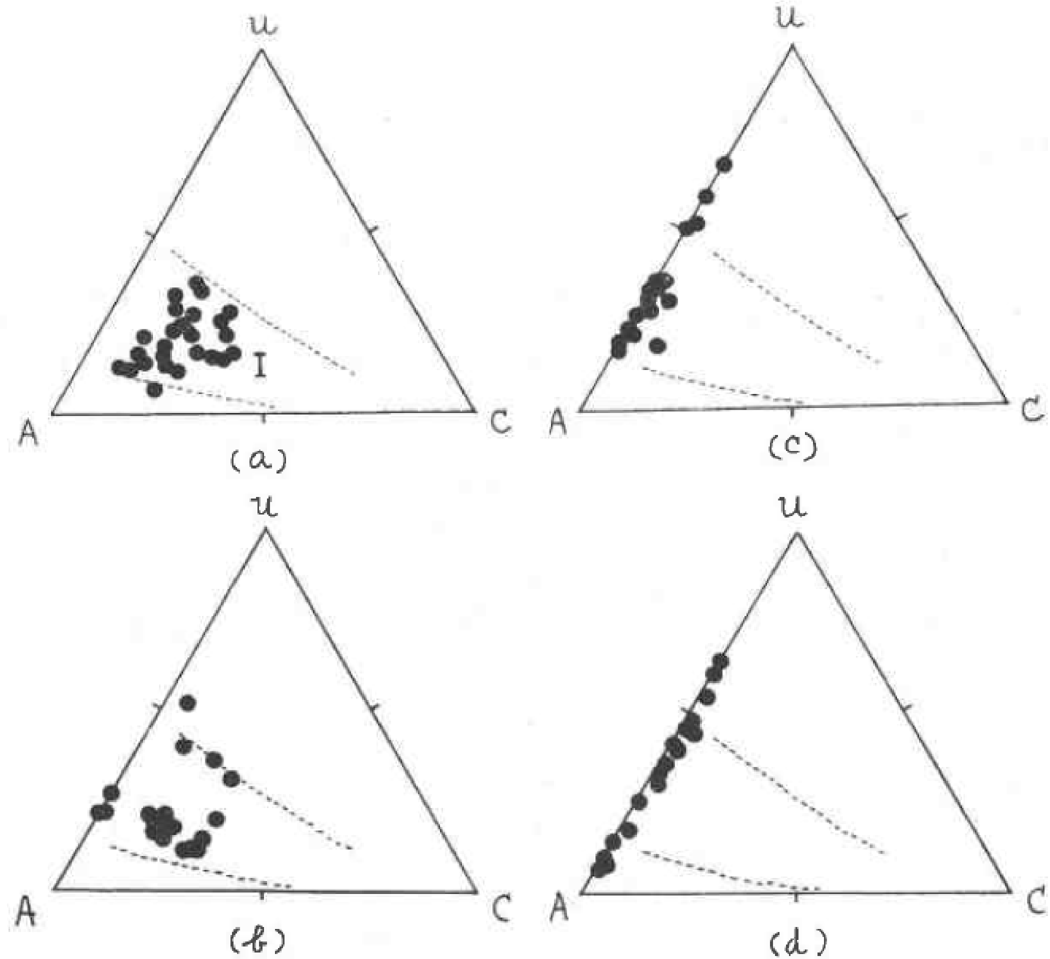
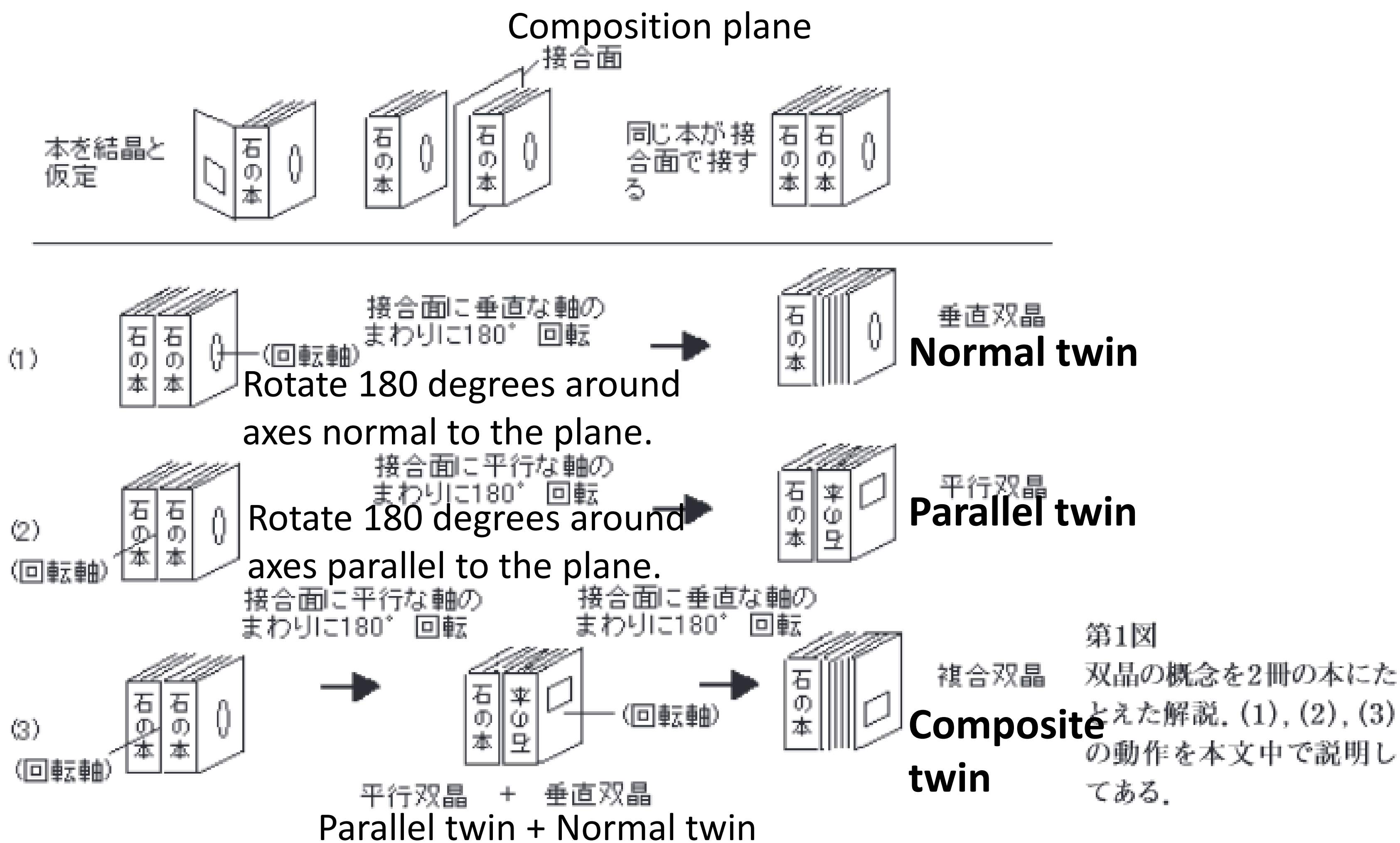


FIG. 13. U:A:C ratios in the plagioclase of various granitic rocks.
(*a*) Granitic rocks occurring as batholiths and stocks.
(*b*) Granitic rocks occurring as dikes and sheets.
(*c*) Granitic rocks occurring as lit-par-lit veins of injection-gneisses.
(*d*) Plutonic-looking rocks of Hida Plateau.
I = Field of typical igneous plagioclase.

Twinning concept



Plagioclase twinning

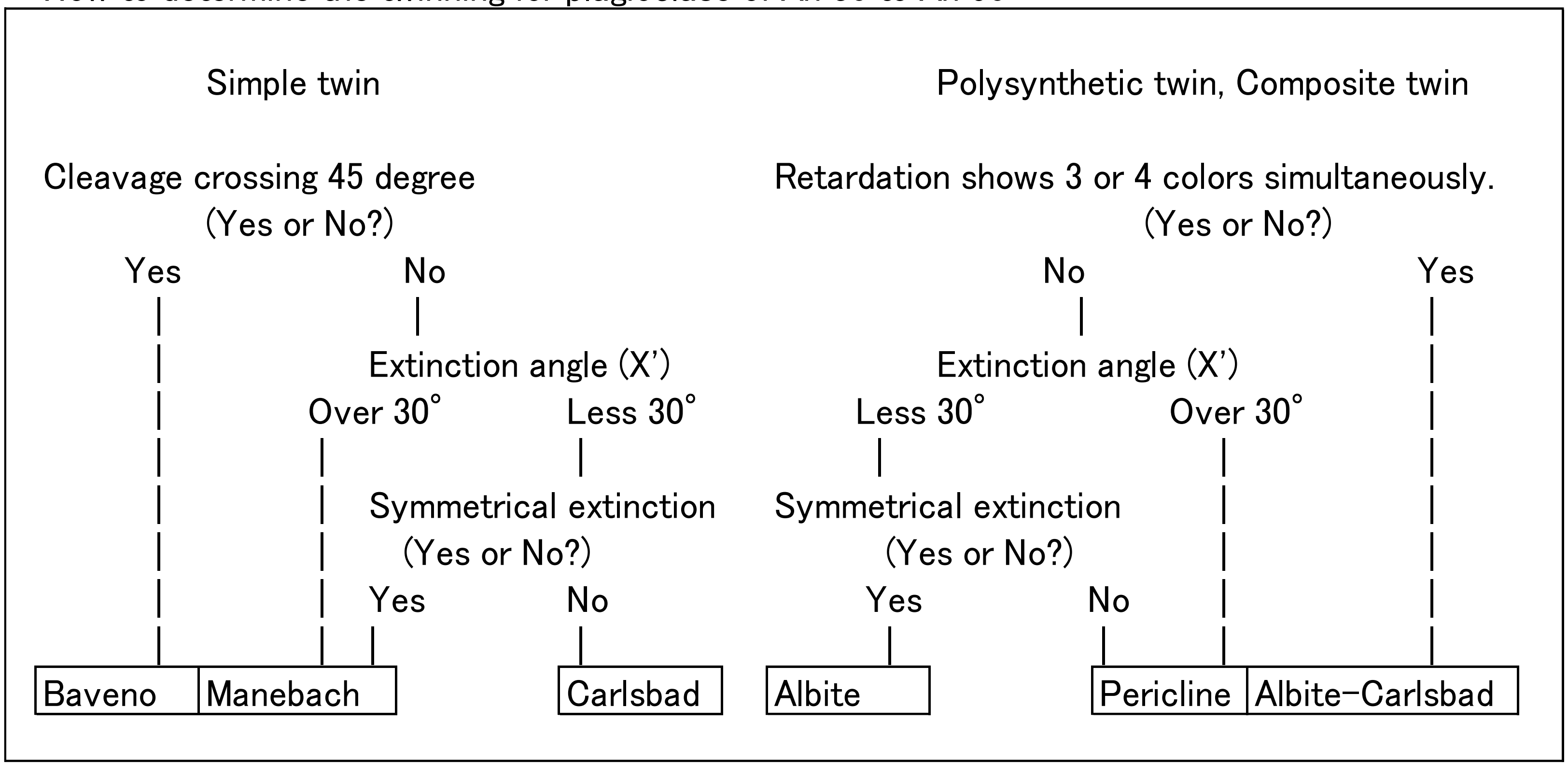
Plagioclase twinning

	Normal twin		Parallel twin		Normal + Parallel
Composition plane	Simple twin	Polysynthetic twin	Simple twin	Polysynthetic twin	Composite twin
(010) (Cleavage)		**Albite**	**Carsbad** (Twin axis; c axis)		**Albite-Carlsbad** Twin axis; normal to c on (010)
(001) (Cleavage)	Manebach			Acline A* (Twin axis; b axis)	
(100)				Acline B (Twin axis; b axis)	
Rhombic section (Including b axis)				**Pericline*** (Twin axis; b axis)	
(021) or (021) Diagonal to cleavage	Baveno				

* Acline A twin and Pericline twin are not distinguished in plagioclase of An30 to An50.
The twins which occur commonly show boldface.

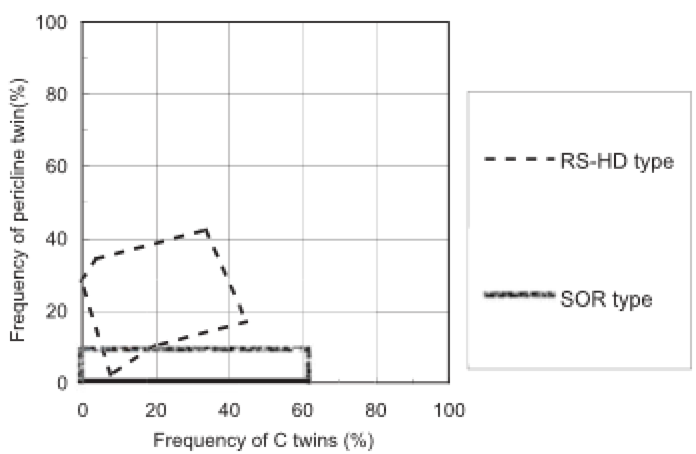
How to determine the twinning for plagioclase of An 30 to An 50

How to determine the twinning for plagioclase of An 30 to An 50



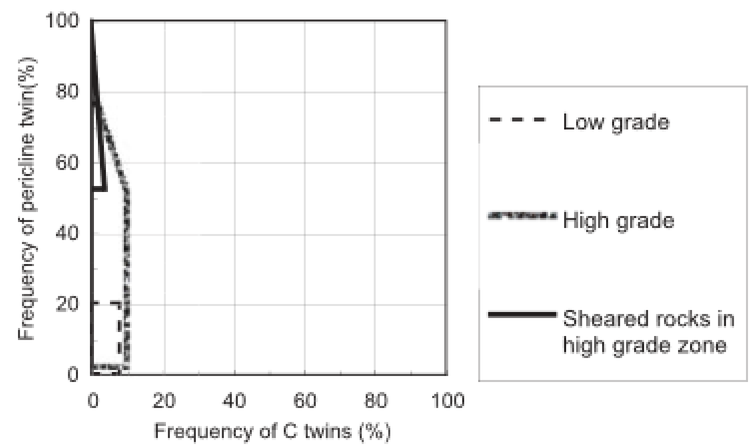
Twinning of plagioclase revisit

Plagioclase twinning were discussed around 1950–1960, however plagioclase twinning should be revisited because of expanding of geological research areas in the world. In addition, description of twinning is base of petrography. The following diagrams were proposed after 2000.



第3図 斜長石双晶に基づく花崗岩類識別図

Fig. 3 Discriminative diagram for granitic rocks based on plagioclase twinning laws

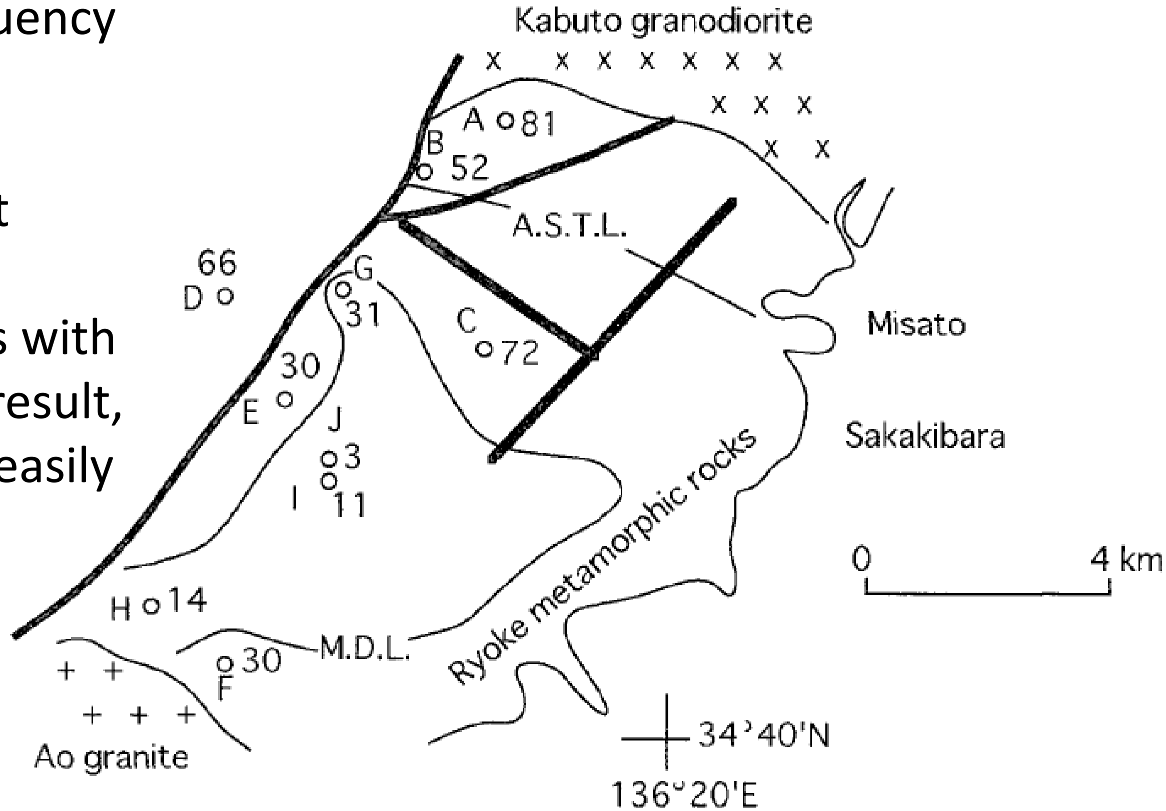


第4図 斜長石双晶に基づく砂泥質(石英長石質)変成岩類識別図

Fig. 4 Discriminative diagram for psamitic to pelitic (quartz-feldspathic) metamorphic rocks based on plagioclase twinning laws

Frequency of pericline twin in the metamorphic rocks in Mie Prefecture, Japan

Pericline twin frequency increases near the granitic rocks. The granitic body might intrude into the metamorphic rocks with shear stress. As a result, pericline twinning easily produced.



第 3 図　津西部地域の領家変成岩類における斜長石双晶中のペリクリン双晶の頻度（%）

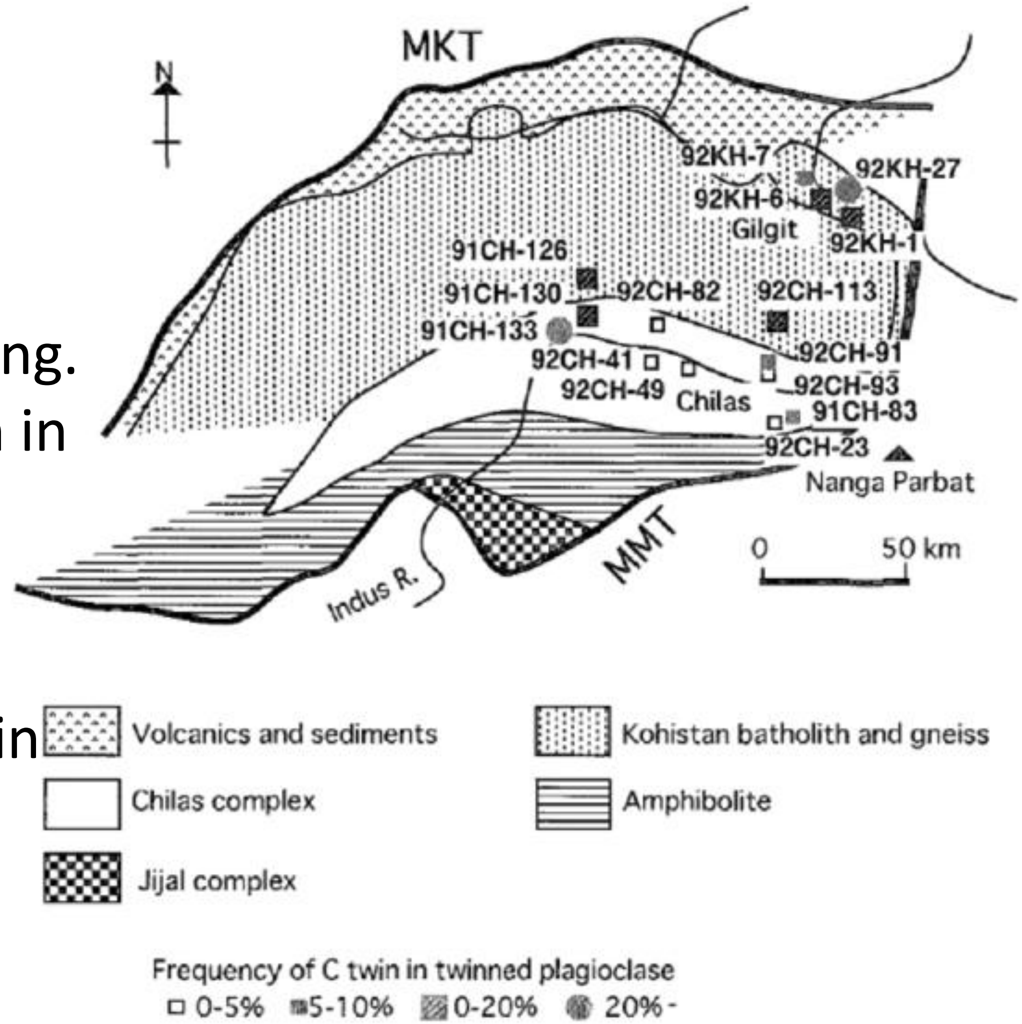
A.S.T.L.；紅柱石珪線石転移線，M.D.L.；白雲母消失線．A から J は第 2 図のものに対応する．

Fig. 3　Frequency of pericline twin in twinned plagioclase of the Ryoke metamorphic rocks in the west of Tsu City

A.S.T.L., andalusite-sillimanite transion line; M.D.L., muscovite disappearance line. A to J correspond to them of Fig. 2.

Chilas Complex in Pakistan

This complex exposed some levels due to folding. C twin frequency is high in central area and low in eastern area.
It is suggested that the deeper part is exposed in east and that the upper part, having igneous character, is exposed in central.

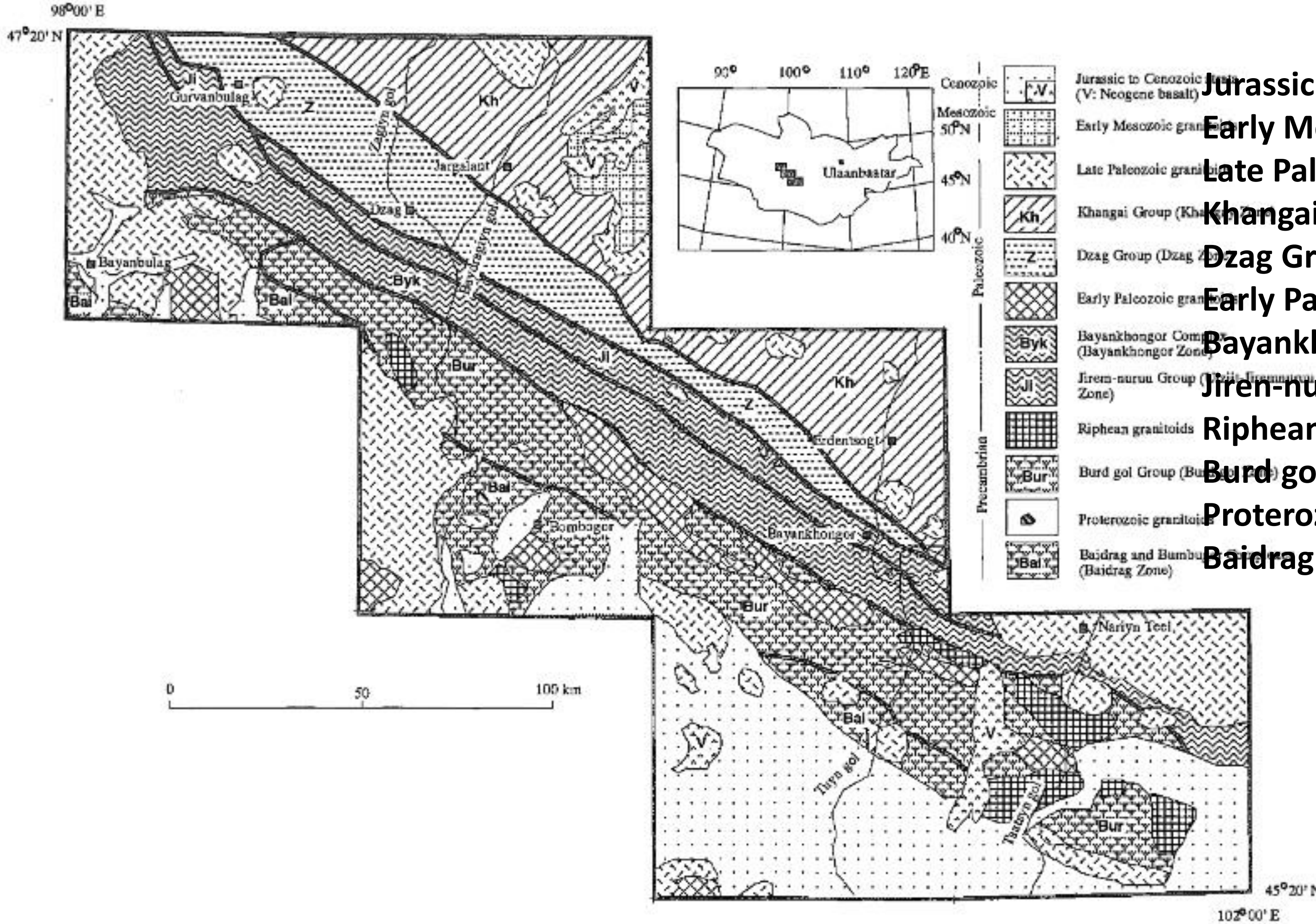


第６図　パキスタン北部，チラス岩体とコヒスタンバソリスの斜長石中のＣ双晶の頻度
Fig. 6　Frequency of C twins in twinned plagioclase in the Chilas complex and Kohistan batholith, northern Pakistan

5. Granitic rocks in central Mongolia

Geological survey was performed in Central Mongolia by Mongolian and Japanese cooperation project in 1995 to 1999. During this survey, concept of accretionary tectonics was donated with microfossil analyses and sandstone petrography. In addition, concept of granitoids series was donated and granite magmatism and mineralization were discussed.

Geology of central Mongolia



Jurassic to Cenozoic
Early Mesozoic Granitoids
Late Paleozoic Granitoids
Khangai Group
Dzag Group
Early Paleozoic Granitoids
Bayankhongor Complex
Jiren-nuruu Group
Riphean Granitoids
Burd gol Group
Proterozoic Granitoids
Baidrag and Bumbuger Complex

Fig. 1 Simplified geologic map Modified from Geology Group of IGMR Project (1999). The word "gol" in this figure means river in Mongolian.

Field occurrences of granites

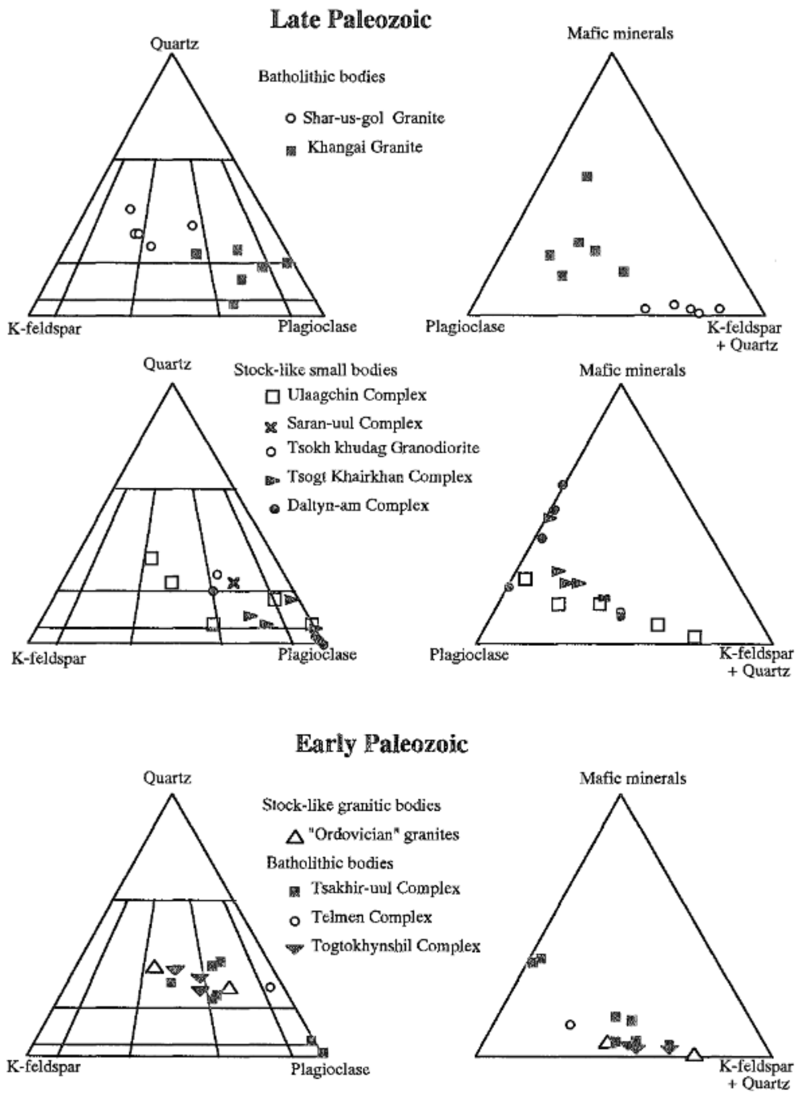


Fig. 2 Modal compositions of the granitoids

Modal analyses of granites

Granites in Early Paleozoic show trending from tonalite to granite through granodiorie.

Granites in Late Paleozoic show trending from quartz monzonite to granite.

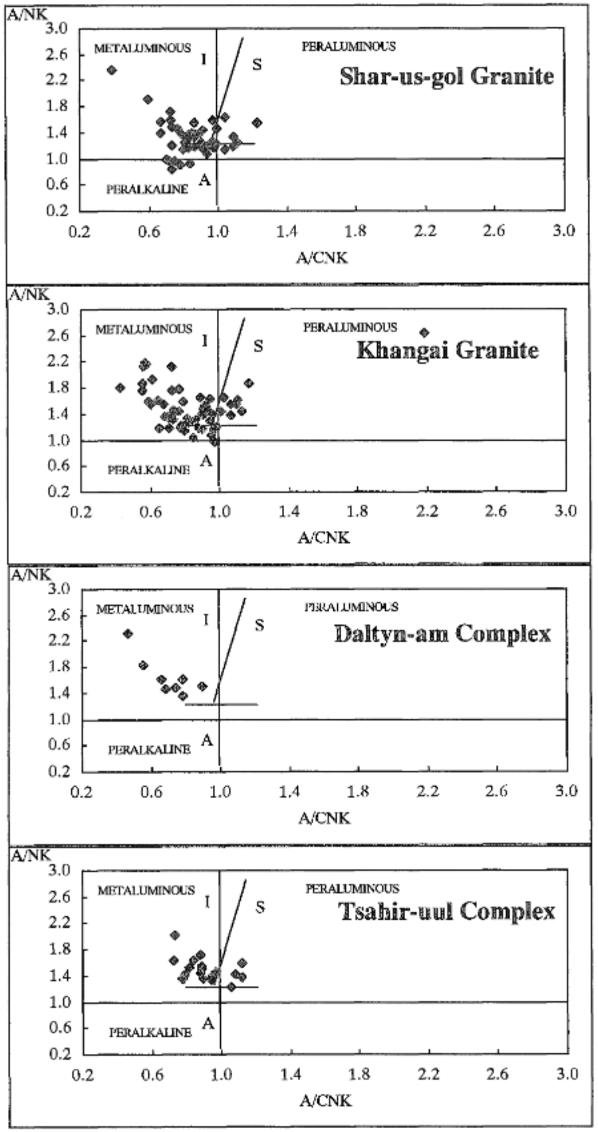


Fig. 3 A/NK vs. A/CNK diagram A/NK: $Al_2O_3/(Na_2O+K_2O)$, A/CNK: $Al_2O_3/(CaO+Na_2O+K_2O)$ in molecule. I, S, and A are fields of I-, S-, and A-type granitoids (Chappel and White, 1977; Collins *et al.*, 1982). Boundaries are modified on the basis of Maeda *et al.* (1986). Chemical data are based upon data in the texts of previous geological maps (e.g., Tumurchudor, 1990; Davaa *et al.*, 1989; Bayarsaihan *et al.*, 1990) and our unpublished data.

A/NK – A/CNK

A/NK: $Al_2O_3/(Na_2O+K_2O)$
A/CNK: $Al_2O_3/(CaO+Na_2O+K_2O)$
(Mole ratio)

This diagram is useful for determining alphabetical classification.
Daltyn-am Complex is I-type.
The other complexes are dominant in I-type characteristic but partly S-type and characteristics.

Geochronology of granites in central Mongolia

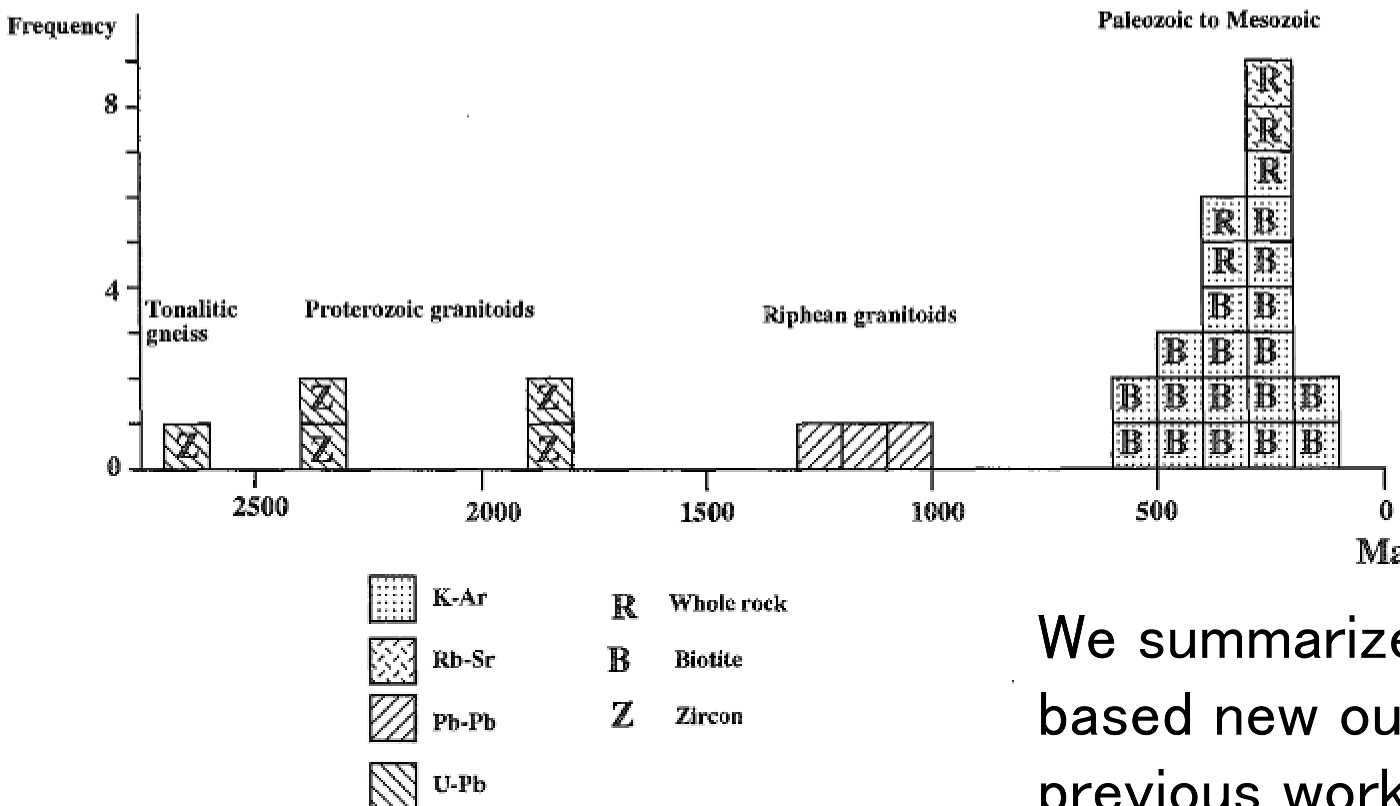


Fig. 4 Histogram of age data

We summarized age data based new our data and previous works' data. This time, methods for determining ages are limited.

Outline of granites in the area

Granitoids in the Bayankhongor area

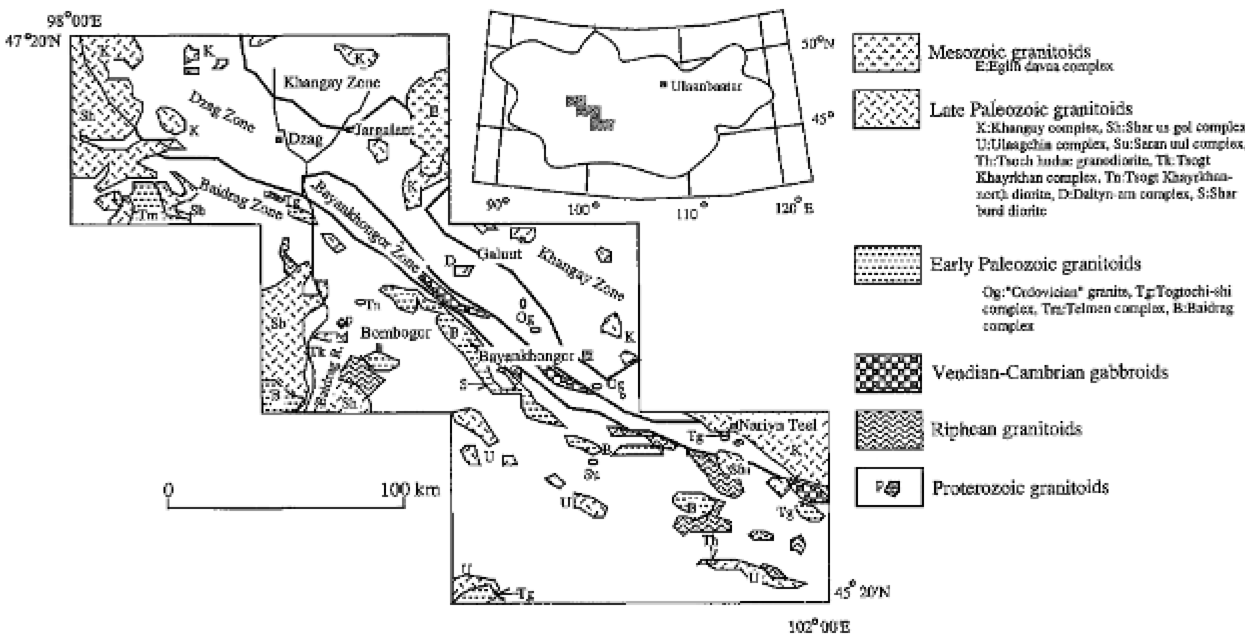


Fig. 1 Geologic map. Simplified and based upon Byamba (1985), State Geological Fund (1995) and Tungalag (1997).

Mesozoic Granitoids
Late Pleozoic Gr

Early Paleozoic Gr

Vendian-Cambrian Gb
Riphean Granitoids
Proterozoic Granitoids

Magnetic susceptibility in granites

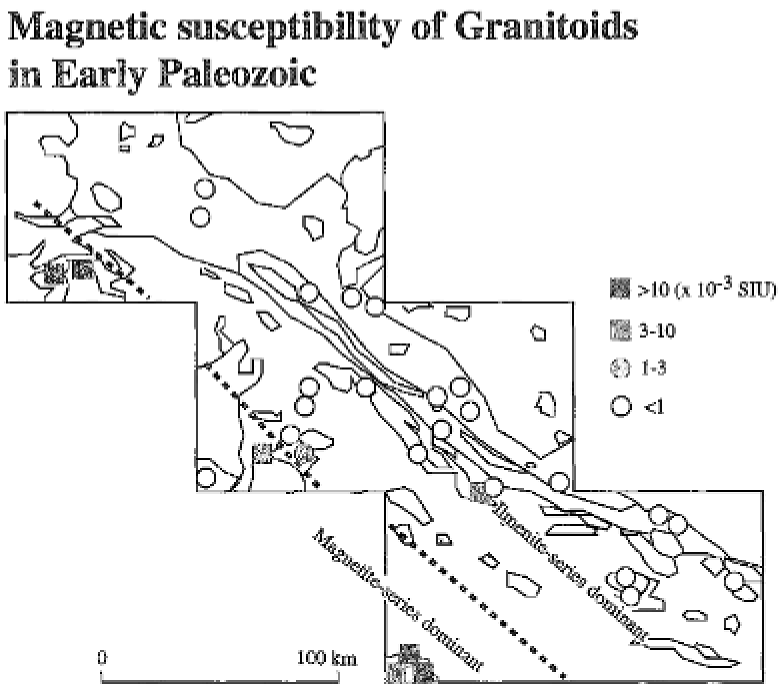


Fig. 2 Magnetic susceptibility of the granitoids in early Paleozoic.

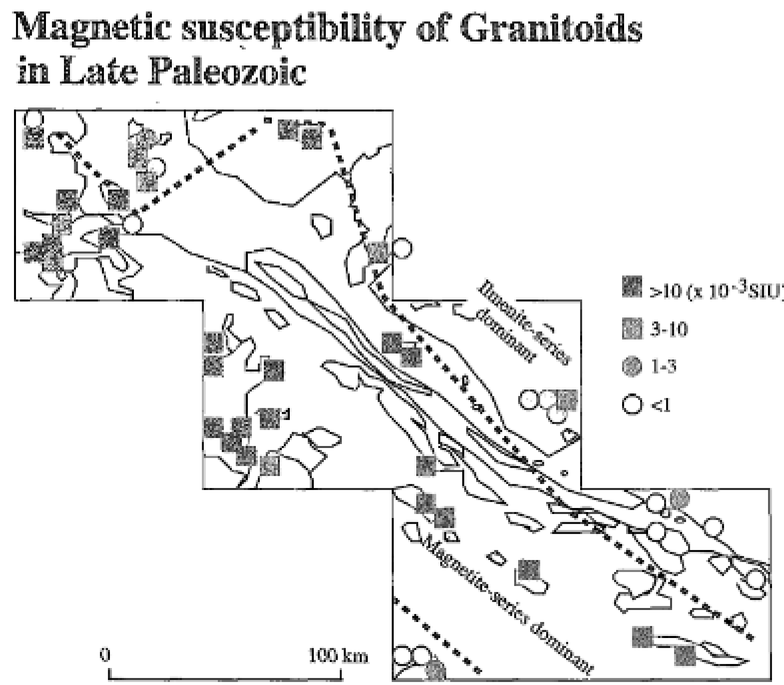


Fig. 3 Magnetic susceptibility of the granitoids in late Paleozoic.

Boundary between magnetite series and ilmenite series shifted northeastward.

Fe_2O_3/FeO

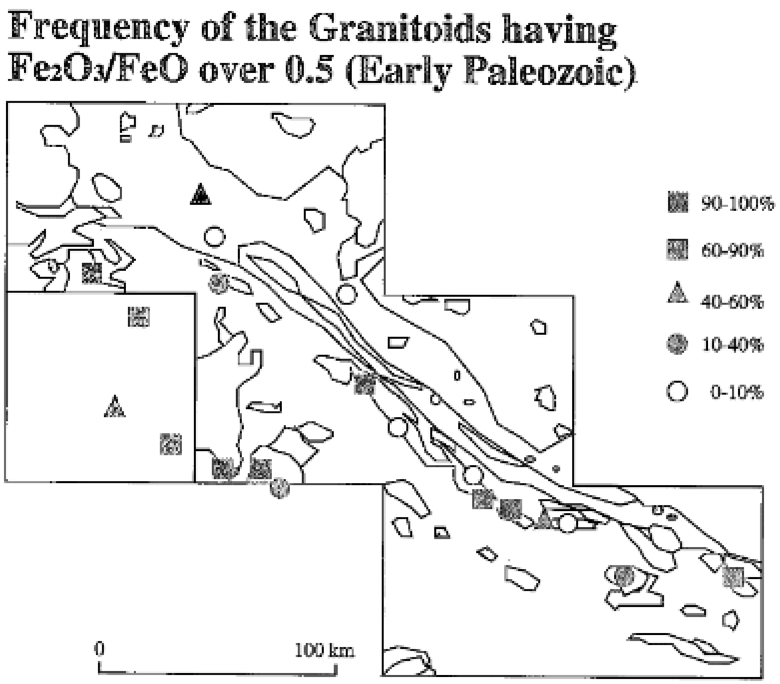


Fig. 5 Frequency of the granitoids having Fe_2O_3/FeO ratio higher than 0.5 (Early Paleozoic).

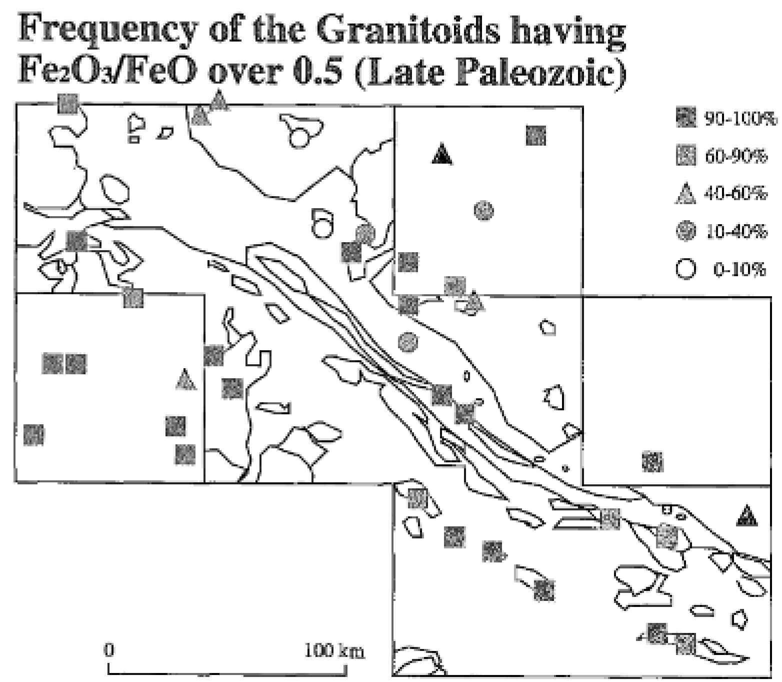


Fig. 6 Frequency of the granitoids having Fe_2O_3/FeO ratio higher than 0.5 (Late Paleozoic).

Variation of Ferric-Ferrous ratio corresponds to variation of granitoids series based magnetic susceptibility.

Summary of granites in central Mongolia

・Ilmenite series granitoids were dominant in Riphean.
・Ilmenite-series granitoids were dominant in Early Paleozoic with minor of magnetite series in southwest.
・Magnetite series granitoids were dominant in Late Paleozoic.

☆Boundary between magnetite series and ilmenite series shifted northeastward from Early Paleozoic to Late Paleozoic. This may correspond to formation of Khangai belt in Middle to Late Paleozoic. Subduction might shift due to formation of accretionary complex (the Khangai belt). As a result, magmatism also shifted toward new subduction position.

・Mesozoic granites were ilmenite series.

Granitoids series in Late Paleozoic

Relationship between metal deposits and granitoids series in Late Paleozoic

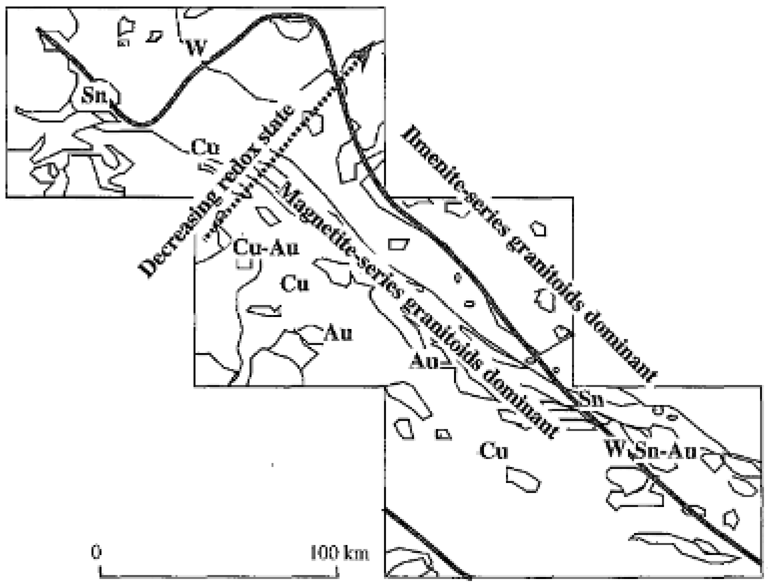


Fig. 7 Relationship between the selected metal deposits and the granitoid series in late Paleozoic.

Copper and gold mineral deposits were distributed in magnetite series granitoids area. Tin and tungsten deposits were distributed near the boundary between magnetite series and ilmenite series or in ilmenite series granitoids area.