# On the Reactivity of Various Silicate Minerals toward Acids

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(Received May 31, 1960)

As for the relative difficulty of dissolution of oxyacids and their salts toward water, a few qualitative rules have been proposed on the standpoint of ionic potential[1]. However, it is not too much to say that no comprehensive treatises on the reactivity of various silicate minerals toward ordinary acids (except hydrofluoric acid) have been reported, although the studies on the individual one have been undertaken by many investigators[2].

Previously, the author pointed out the requirements for the frothing reaction of silicate minerals toward water and concentrated sulfuric acid. Those requirements were summarized as follows: 1) the silicates belonging to either the neso- or the phyllo-silicates are generally reactive; 2) in the phyllosilicates, most of those of the 1:1 type (e. g., serpentine) are as a rule reactive, but those of the 2:1 type are not at all or only slightly reactive; and 3) the more electropositive the metallic components are, the more reactive the silicates become. But the electropositivity of metals was not discussed in detail.

1) G. H. Cartledge, *J. Am. Chem. Soc.*, **50**, 2855 (1928); V. M. Goldschmidt, *J. Chem. Soc.*, **1937**, 655; F. E. Wickman, *Arkiv. Kemi, Min. Geol.*, **19B**, No. 2 (1944); R. Tsuchida, *Chemistry (Kagaku)*, **6**, 6 (1951); **7**, 88 (1952).

2) W. Eitel, "The Physical Chemistry of the Silicates", The University of Chicago Press, Chicago, Illinois (1954), p. 965; S. Nagai and Y. Arai, *Gypsum and Lime (Sekko to Sekai)*, **34**, 7 (1958); J. Ando, *J. Chem. Soc. Japan, Ind. Chem. Sec. (Kogyo Kagaku Zasshi)*, **63**, 83 (1960).

In this paper, the author attempted to make this problem clear by using various terms concerning the combining forces between the cations and the silicate ions, and also to explain it energetically from the bonding energies of silicate minerals.

## Results from the Electropositivity of the Constituent Metals

It is well known in the field of crystal chemistry that the bonding force between various cations and silicate ions is related to the polarizing power of the cations or their tendencies to form covalent bonds with oxygen atoms. One may say that a cation with strong polarizing power or a pronounced tendency to make covalent bonds loosens bonds within a silicate ion, thus causing a splitting up of it into free acids. On the contrary, cations with small polarizing power allow strong bonds to form within the silicate ion and do therefore make stable silicate.

This polarizing power of cations is qualitatively or approximately measured with their ionic potentials (e. g., cation charge/cation radius), the ratio of cation charge to the square of cation radius (Goldschmidt's polarizing power), or the field strength around the cations[3], etc. (hereafter referred to as $\phi$, $\phi'$ or F. S., respectively.)

Therefore, the author tried to calculate and to view the above mentioned values of various cations contained in silicate minerals. The results were listed in the following table[4].

| | | |
|---|---|---|
| $\phi$; | more than 4 | Ti, Be, Al, Cr, V(III), Zr, Fe(III), Mn(III). |
| | 3~4 | Th, Sc. |
| | 2~3 | Y, Mg, Ni, Ce, La, Fe(II), Zn, Mn(II). |
| | less than 2 | Cu, Ca, Sr, Pb, Ba, Li, Na, K. |
| $\phi'$; | more than 6 | Be, Ti, Al, Cr, V(III), Fe(III), Mn(III). |
| | 4~6 | Zr, Sc. |
| | 2~4 | Th, Mg, Ni, Y, Fe(II), Zn, Mn(II), Ce, La. |
| | less than 2 | Cu, Ca, Li, Sr, Pb, Na, Ba, K. |
| F. S.; | more than 0.7 | Ti, Th, Al, Cr, Zr, V(III), Fe(III), Be, Mn(III). |
| | 0.5~0.7 | Sc, Y. |
| | 0.4~0.5 | Ce, La, Mg, Ni, Fe(II), Zn, Mn(II). |
| | less than 0.4 | Cu, Ca, Sr, Pb, Ba, Li, Na, K. |

As shown in this table, the polarizing power of the following cations seems to be extremely great, and further the electropositivity of them to be small: e. g., Ti, Be, Al, Cr, V(III), Fe(III), Mn(III), Zr, etc. Thus the existence of these metals may contribute to the decrease of reactivity of silicate minerals. This conclusion is in agreement with the experimental results that kaolinite is not completely decomposed, although serpentine is easily attacked by acids.

As is generally known, all the silicate minerals were now divided into five classes structurally; namely, neso-, soro-, ino-, phyllo-, and tecto-silicate. According to this classification, it was at first in Tables I—V[5] examined whether or not the singularity of the above eight metal ions is applicable to those silicates. In Tables I—V the results of reactions toward acids are made an entry. Most of them are cited from the data of Lange's Handbook[6], Dana's Textbook of Mineralogy[7], and Mellor's Treatise[8]. The parenthesized passage is refered to the author's prediction.

**Nesosilicate Minerals.**—The nesosilicates are termed the silicates having the structures with separated tetrahedra $(SiO_4)^{4-}$ groups, and involve the following minerals listed in Table I.

Generally speaking, the results in Table I seem to indicate that the majority of nesosilicate minerals are able to react with acids, and to be decomposed with the formation of gelatinous silica, except the garnet group and a few particular complex silicate minerals. Also it is confirmed that one of the above eight metallic elements is inevitably contained in these insoluble nesosilicate minerals.

For example, phenacite ($Be_2SiO_4$) is not attacked by acids. This fact is probably due to the existence of Be atoms, which have very large $\phi$, $\phi'$ and F. S. For the same reason, the garnet group minerals, euclase, topaz, zunyite, andalusite, sillimanite, mullite, kyanite, sapphirine, etc. may be not decomposed by acids. Moreover titanosilicate minerals containing Ti atoms are inactive toward acids. Although

3) A. Dietzel, *Naturwiss.*, **29**, 537 (1941); *Electrochem.*, **48**, 9 (1942).

4) The values of the ionic radii of various cations were quoted from C. W. Stillwell's "Crystal Chemistry", McGraw-Hill Book Co., Inc., New York (1938).

5) The classification, species and structural formula of silicate minerals are based upon Sudo's system (which is primarily cited from Berman's and Swartz's systems and is revised and enlarged with the latest data.) and Strunz's Tables (H. Strunz, "Mineralogische Tabellen" (1958)).

H. Berman, *Am. Mineralogist*, **22**, 342 (1937); O. K. Swartz, ibid., **22**, 1073, 1161 (1937); T. Sudo, "Mineral Chemistry (Kobutsu Kagaku) (II)", Kyoritsu Shuppan Co., Ltd. (1959), p. 259.

6) Lange's Handbook of Chemistry (1949).

7) Dana's Textbook of Mineralogy (1959).

8) W. Mellor, "A Comprehensive Treatise on Inorganic and Theoretical Chemistry", Vol. VI (1925).

TABLE I. REACTIVITY OF NESOSILICATE MINERALS TOWARD ACIDS

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| Olivine series (Ca, Mn, Mg, Fe, Pb) (Mg, Fe, Mn, Zn) $SiO_4$ | | | |
| Forsterite | $Mg_2SiO_4$ | Gel. a. | 29796 |
| Olivine | $(Mg, Fe)_2SiO_4$ | Gel. a. | (29904) *1) |
| Hortonolite | $(Mg, Fe, Mn)_2SiO_4$ | Gel. a. | |
| Fayalite | $Fe_2SiO_4$ | Gel. a. | (29880) |
| Knebelite | $(Fe, Mn)_2SiO_4$ | Gel. a. | |
| Tephroite | $(Mn, Zn, Mg)_2SiO_4$ | Gel. a. | |
| Roepperite | $(Fe, Mn, Zn)_2SiO_4$ | Gel. HCl | |
| Glaucochroite | $CaMnSiO_4$ | Gel. HCl | |
| Monticellite | $CaMgSiO_4$ | Gel. HCl | (29358) |
| Larsenite | $PbZnSiO_4$ | Sol. $HNO_3$ | |
| Calcium Larsenite | $(Pb, Ca)ZnSiO_4$ | Sol. $HNO_3$ | |
| Larnite | $Ca_2SiO_4$ | Sol. HCl | (28920) |
| Merwinite | $Ca_3Mg(SiO_4)_2$ | Sol. HCl | (29139) |
| Phenacite group $X_2SiO_4$ | | | |
| Phenacite | $Be_2SiO_4$ | Insol. | |
| Willemite | $Zn_2SiO_4$ | Gel. a. | |
| Troostite | $(Zn, Mn)_2SiO_4$ | Gel. a. | |
| Trimerite | $CaMn_2(BeSiO_4)_3$ | Sol. HCl | |
| Humite group $nMg_2SiO_4 \cdot Mg(OH, F)_2$ | | | |
| Norbergite | $Mg_2SiO_4 \cdot Mg(OH, F)_2$ | Gel. a. | (27632) *2) |
| Chondrodite | 2 〃 · 〃 | Gel. a. | (28498) *2) |
| Humite | 3 〃 · 〃 | Gel. a. | (28869) *2) |
| Clinohumite | 4 〃 · 〃 | Gel. a. | (29075) *2) |
| Hodgkinsonite group $X_{2r+1}(SiO_4)_r(OH, F)_2$ | | | |
| Hodgkinsonite | $(Zn_2Mn)(SiO_4)(OH)_2$ | Sol. a. | |
| Alleghanyite | $Mn_5(SiO_4)_2(OH, F)_2$ | Sol. a. | |
| Leucophoenicite | $Mn_7(SiO_4)_3(OH)_2$ | Sol. a. | |
| Garnet group $X_3Y_2(ZO_4)_3$ | X=Mg, Fe, Mn, Ca<br>Y=Al, Fe(III), Cr, Ti, Mn<br>Z=Si, Ti | | |
| (1) Almandite series $(Mg, Fe, Mn)_3Al_2(SiO_4)_3$ | | | |
| Pyrope | $Mg_3Al_2(SiO_4)_3$ | Insol. | (31836) |
| Almandite | $Fe_3Al_2(SiO_4)_3$ | Insol. | 31878 |
| Spessartite | $Mn_3Al_2(SiO_4)_3$ | Insol. | |
| (2) Andradite series | | | |
| Grossularite | $Ca_3Al_2(SiO_4)_3$ | Insol. | (31398) |
| Andradite | $Ca_3Fe_2(SiO_4)_3$ | Insol. | |
| Uvarovite | $Ca_3Cr_2(SiO_4)_3$ | Insol. | |
| Titanium Garnet | $Ca_3(Al, Fe(III), Fe(II), Ti)_2[(Si, Ti)O_4]_3$ | Insol. | |
| Zircon group $XSiO_4$ | | | |
| Zircon | $ZrSiO_4$ | Mostly insol. | |
| Thorite | $ThSiO_4$ | Gel. a. | |
| Wöhlerite group $W_3X(ZO_4)_2(F, OH)$ | | | |
| Rosenbuschite | $(Na, Ca)_3(Fe, Ti, Zr)(SiO_4)_2F$ | Sol. HCl | |
| Wöhlerite | $(Ca, Na)_3(Zr, Ta)(SiO_4)_2F$ | Sol. HCl | |
| Hiortdahlite | $(Ca, Na)_3(Fe, Mn, Zr, Ti)(SiO_4)_2(F, OH)$ | (Sol. HCl) | |
| Guarinite | $(Ca, Na)_3(Fe, Mn, Zr, Ta)(SiO_4)_2(O, F, OH)$ | Gel. HCl | |
| Johnstrupite | $(Ca, Na, Ce)_3(Al, Mg, Ti, Ce)(SiO_4)_2(F, OH)$ | Sol. HCl | (29850) *3) |
| Rinkite | $(Ca, Na)_6(Ce, Zr, Ti)_7(SiO_4)_{10}F_7$ | Decomp. $H_2SO_4$ | |
| Rinkolite | $(Ca, Na)_6(Ce, Ti)_3(SiO_4)_4(F, OH)_4$ | (Decomp. a.) | |
| Mosandrite | $(Ca, Na)_{12}Ce_3(Zr, Ti, Mg)_4(SiO_4)_{10}F_5$ | Sol. HCl | |
| Låvenite | $(Ca, Na)(Zr, Ta, Fe, Ti, Mn)(SiO_4)F$ | Sl. sol. HCl | |
| Britholite | $Ca_3Ce_4[(Si, P)O_4]_4(OH, F)_3$ | (Decomp. a.) | |
| Hellandite | $Ca_3(Y, Er)_4(Al, Fe(III), Mn(III))_5(SiO_4)_6(OH)_9$ | Sol. HCl | |

TABLE I. (Continued)

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| Lessingite | $Ca_2(Ce, La, Na)_3(SiO_4)_3(OH, F)$ | (Decomp. a.) | |
| Beckelite | | Sol. a. | |
| Datolite group | | | |
| Datolite | $Ca_2B_2(SiO_4)_2(OH)_2$ | Gel. HCl | |
| Euclase | $Al(BeOH)SiO_4$ | Insol. | |
| Homilite | $Ca_2Fe(II)Be_2(SiO_4)_2O$ | Gel. HCl | |
| Gadolinite | $Y_2Fe(II)Be_2(SiO_4)_2O_2$ | Gel. a. | |
| Misc. | | | |
| Topaz | $Al_2SiO_4(F, OH)_2$ | Sl. decomp. $H_2SO_4$ | 31712 |
| Ilvaite | $Ca(Fe, Mn)_2Fe(III)(SiO_4)_2(OH)$ | Gel. a. | |
| Afwillite | $Ca_3(SiO_3OH)_2\cdot 2H_2O$ | (Decomp. a.) | |
| $\alpha$-Eucryptite | $\alpha$-$LiAl(SiO_4)$ | Gel. HCl | |
| Eulytite | $Bi_4(SiO_4)_3$ | Gel. HCl | |
| Zunyite | $Al_{12}(Si_2O_7)_2(SiO_4)(AlO_4)(OH, F)_{18}Cl$ | Insol. | |
| Quasi-silicates | | | |
| Aluminum silicates | | | |
| Andalusite | $Al_2SiO_5$ | Insol. | |
| Sillimanite | $Al_2SiO_5$ | Insol. | 31957 |
| Mullite | $(Al_2O)_6(SiO_4)_6(Al_2O_7)$ | Insol. | |
| Kyanite | $Al_2SiO_5$ | Insol. | |
| Staurolite | $Fe(II)Al_4Si_2O_{10}(OH)_2$ | Sl. decomp. $H_2SO_4$ | 31828 |
| Kentrolite group | | | |
| Kentrolite | $Pb_3Mn(III)_4Si_3O_{15}$ | Sol. a. | |
| Melanotekite | $Pb_3Fe(III)_4Si_3O_{15}$ | Decomp. $HNO_3$ | |
| Titanosilicates | | | |
| Titanite | $CaTiSiO_5$ | Sol. $H_2SO_4$ | (32942) |
| Lorenzenite | $Na_2(Zr, Ti)_2Si_2O_9$ | Insol. HCl | |
| Ramsayite | $Na_2Ti_2Si_2O_9$ | (Insol.) | (33845) |
| Lamprophyllite | $Na_3Sr_2Ti_3(SiO_4)_4(O, OH, F)_2$ | (Insol.) | |
| Fersmanite | $Ca_4Na_4Ti_4Si_3O_{18}F_2$ (?) | (Insol.) | |
| (App.) | | | |
| Dumortierite | $(Al, Fe)_7BSi_3O_{18}$ | Insol. HF | |
| Serendibite | $(Ca, Mg)_5Al_5BSi_3O_{20}$ | (Insol.) | |
| Sapphirine | $Mg_2Al_4SiO_{10}$ | Insol. | (31283) |
| Ardennite | $Mn_5Al_5(V, As)O_4Si_5O_{20}(OH)_2\cdot 2H_2O$ | (Insol.) | |
| Kornerupine | $(Mg, Fe, Al)_4(Al, B)_6Si_4O_{16}(O, OH)_{5\sim 6}$ | (Insol.) | |
| Cappelenite | $(Ba, Ca, Ce, Na)_3(Y, Ce, La)_6B_6Si_3O_{27}$ | Sol. HCl | |
| Melancocerite | $Ca_{16}Na_4(Y, La)_3(Zr, Ce)_6B_3Si_{12}O_{57}F_{12}$ | Decomp. HCl | |
| Uranosilicates | | | |
| Uranophane | $Ca(H_3O)_2(UO_2)(SiO_4)_2\cdot 3H_2O$ | Gel. HCl | |
| Sklodowskite | $MgU_2O_2(OH)_2(SiO_4)_2\cdot 4H_2O$ | Gel. HCl | |
| Kasolite | $PbUO_2SiO_4\cdot H_2O$ | Gel. a. | |
| Soddyite | $(UO_2)_2SiO_4\cdot 2H_2O$ (?) | Gel. HCl | |

(Abbreviations used in Tables I—V.)

a.: acids; abbr.: abbreviation; app.: appendix; conc.: concentrated; decomp.: decomposed (by); gel.: gelatinize; insol.: insoluble (in, or, in acids); misc.: miscellanea; sl.: slightly; sol: soluble (in); undecomp.: undecomposed (by).

(The minerals cited in the appendixes in these tables are unassigned up to the present.)

*1) This value was calculated regarding the compositional formula of olivine as $9Mg_2SiO_4\cdot Fe_2SiO_4$.

*2) These values were calculated regarding $nMg_2SiO_4\cdot Mg(OH, F)_2$ as $nMg_2SiO_4\cdot Mg(OH)_2$.

*3) This value was calculated regarding the chemical formula of johnstrupite as ideally $Ca_3Al(SiO_4)_2(OH)$.

TABLE II. REACTIVITY OF SOROSILICATE MINERALS TOWARD ACIDS

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| Benitoite | $BaTi(Si_3O_9)$ | Sol. HF | |
| Rhodonite series | | | |
| Rhodonite | $(Mn, Ca)_5Si_5O_{15}$ | Sl. sol. HCl | |
| Pyroxmangite | $(Mn, Ca)_7Si_7O_{21}$ | Insol. a. | |
| Wollastonite group | | | |
| Wollastonite | $Ca_3Si_3O_9$ | Decomp. HCl | |
| Bustamite | $(Ca, Mn)_3Si_3O_9$ | (Decomp. HCl) | |
| Pectolite | $Ca_2NaH(SiO_3)_3$ | Gel. HCl | |
| Alamosite | $PbSiO_3$ | (Gel. $HNO_3$) | |
| Catapleiite series | | | |
| Catapleiite | $Na_2Zr(Si_3O_9)\cdot H_2O$ | Sol. HCl | |
| Eudialyte | $(Na, Ca, Fe)_6ZrSi_6O_{18}(OH, Cl)$ | Gel. HCl | |
| Steenstrupine | $(Ca, Na)_4Mn(Ce, La, Al, Fe(III))_6(Si, Ti)_9O_{27}(OH)_7\cdot 3H_2O$ (?) | Decomp. a. | |
| Tourmaline series $WX_3Y_6(Z_3O_9)_3(O, OH, F)_4$ | | | |
| Dravite | $NaMg_3B_3Al_3(Al_3Si_6O_{27})(OH)_4$ | Undecomp. a. | |
| Uvite | $CaMg_3B_3Al_3(Al_3Si_6O_{27})(O, OH)_4$ | Undecomp. a. | |
| Indigolite | $Na(Al, Fe(II), Li, Mg)_3B_3Al_3(Al_3Si_6O_{27})(O, OH, F)_4$ | Undecomp. a. | |
| Tourmaline | $(Na, Ca)(Mg, Fe(II), Fe(III))_3B_3Al_3(Al_3Si_6O_{27})(O, OH)_4$ | Undecomp. a. | |
| Schorl | $NaFe_3B_3Al_3(Al_3Si_6O_{27})(OH)_4$ | Undecomp. a. | |
| Misc. | | | |
| Dioptase | $Cu_6(Si_6O_{18})\cdot 6H_2O$ | Gel. HCl | |
| Axinite | $(Fe, Mn)Ca_2Al_2(BO_3)(Si_4O_{12})(OH)$ | Undecomp. a. | |
| Beryl | $Al_2Be_3Si_6O_{18}$ | Insol. | |
| Osumilite | $(K, Na, Ca)(Mg, Fe(II))_2(Al, Fe(III), Fe(II))_3(Si, Al)_{12}O_{30}\cdot H_2O$ | (Sl. decomp. a.) | |
| Indialite | $(Mg, Fe)_2Al_3(Si_5, Al)O_{18}$ | (Sl. decomp.) | (31920)*1) |
| Cordierlite | $(Mg, Fe)_2Al_3(Si_5, Al)O_{18}$ | Sl. decomp. a. | (31920)*1) |
| Thalenite group | | | |
| Thalenite | $Y_2Si_2O_7$ | (Insol. a.) | |
| Thortveiteit | $(Sc, Y)_2Si_2O_7$ | Insol. HCl | |
| Cerite | $(Ce, Y, Pr, Nd)_2Si_2O_7\cdot H_2O$ | Gel. HCl | |
| Rowlandite | $(Y, Ce, La)_4Fe(II)(Si_2O_7)_2F_2$ | Gel. HCl | |
| Melilite series | | | |
| Åkermanite | $Ca_2MgSi_2O_7$ | Gel. HCl | 30391 |
| Gehlenite | $Ca_2Al(AlSiO_7)$ | Gel. HCl | 26890 |
| Melilite | $(Ca, Na)_2(Al, Mg)(Si, Al)_2O_7$ | Gel. HCl | |
| Hardystonite | $Ca_2ZnSi_2O_7$ | Gel. HCl | |
| Leucophanite | $(Ca, Na, H)_2BeSi_2O_6(OH, F)$ (?) | Sol. HF | |
| Meliphanite | $(Ca, Na)_2(Be, Al)Si_2O_6F$ | (Insol.) | |
| Barysilite group | | | |
| Barysilite | $Pb_3Si_2O_7$ | Gel. $HNO_3$ | |
| Ganomalite | $Pb_6Ca_4(Si_2O_7)_3(OH)_2$ | Gel. $HNO_3$ | (27383)*2) |
| Nasonite | $Pb_6Ca_4(Si_2O_7)_3Cl_2$ | Gel. $HNO_3$ | |
| Hemimorphite group | | | |
| Hemimorphite | $Zn_4(OH)_2Si_2O_7\cdot H_2O$ | Gel. a. | |
| Clinohedrite | $Ca_2Zn_2Si_2O_7(OH)_2\cdot H_2O$ | Gel. HCl | |
| Bertrandite | $Be_4Si_2O_7(OH)_2$ | Insol. a. | |
| Cuspidine | $Ca_4Si_2O_7(F, OH)_2$ | (Gel. HCl, $HNO_3$) | (28427)*3) |
| Molybdophyllite | $Pb_2Mg_2Si_2O_7(OH)_2$ | (Gel. $HNO_3$) | |
| Murmanite | $NaTiSiO_4(OH)$ (?) | (Insol. a.) | (32,164) (?) |
| (App.) | | | |
| Barylite | $BaBe_2Si_2O_7$ | Insol. | |
| Lawsonite | $CaAl_2Si_2O_7(OH)_2\cdot H_2O$ | Insol. | (31,030) |
| Danburite | $CaB_2Si_2O_8$ | Sl. decomp. HCl | |

TABLE II. (Continued)

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| Astrophyllite | $(K_2, Na_2, Ca)(Fe, Mn)_4 (Ti, Zr)Si_4O_{14}(OH)_2$ | Decomp. HCl | |
| Aenigmanite | $(Na, Ca, K)_4(Fe(II), Mn, Fe(III), Ti, Al)_{13}(Si_2O_7)_6$ (?) | Sl. sol. a. | |
| Vesuvianite | $Ca_{10}Al_4(SiO_4)_5(Si_2O_7)_2 \cdot 2(Mg, Fe)(OH)_2$ | Sl. decomp. HCl | |
| Epidote group $W_2Y_3(ZO_4)(OH)(Z_2O_7)O$ | | | |
| Zoisite | $Ca_2Al_3(SiO_4)(Si_2O_7)O(OH)$ | Insol.*4) | |
| Epidote series | | | |
| Clinozoisite | $Ca_2Al_3(SiO_4)(Si_2O_7)O(OH)$ | Insol. | |
| Epidote | $Ca_2(Al, Fe)_3(SiO_4)(Si_2O_7)O(OH)$ | Sl. decomp. HCl | |
| Piedmontite | $Ca_2(Al, Fe, Mn)_3(SiO_4)(Si_2O_7)O(OH)$ | (Sl. decomp. a.) | |
| Allanite series | | | |
| Allanite | $(Ca, Ce, La, Na)_2(Al, Fe, Mn, Be, Mg)_3(SiO_4)(Si_2O_7)O(OH)$ | Gel. HCl | |
| Nagatelite | $(Ca, Ce)_2(Al, Fe(III), Fe(II))_3[(P, Si)O_4][(P, Si)_2O_7]O(OH)$ | Sol. HCl, $HNO_3$ | |
| Pumpellyite | $Ca_4(Mg, Fe, Mn)(Al, Fe, Ti)_5Si_6O_{23}(OH)_3 \cdot 2H_2O$ | (Sol. HCl ) | |

*1) These values were calculated regarding $(Mg, Fe)_2Al_3(Si_5, Al)O_{15}$ as $Mg_2Al_3(Si_5, Al)O_{18}$.
*2) This value was calculated regarding the chemical formula of ganomalite as $Ca_{10}(Si_2O_7)_3(OH)_2$.
*3) This value was calculated regarding ……$(F, OH)_2$ as ……$(OH)_2$.
*4) The fine powder of zoisite is completely decomposed by boiling hydrochloric acid.

TABLE III. REACTIVITY OF INOSILICATE MINERALS TOWARD ACIDS

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| Pyroxene group $W(X, Y)(Z_2O_6)$ | W=Ca, Na, K, Mg, Mn. X, Y=Mg, Fe(II), Al, Ti, Li, Mn, Fe(III), Cr, Ni. Z=Si, Al. | | |
| (1) Enstatite series $WXZ_2O_6$ | | | |
| Enstatite | $Mg_2Si_2O_6$ | Insol. HCl | 32344 |
| Hyperthene | $(Mg, Fe)_2Si_2O_6$ | Insol. a. | |
| (2) Pigeonite series | | | |
| Clinoenstatite | $Mg_2Si_2O_6$ | Insol. a. | |
| Pigeonite | $(Ca, Mg)(Mg, Fe)Si_2O_6$ | (Insol. a.) | |
| (3) Diopside series $W(X, Y)Z_2O_6$ | | | |
| Diopside | $CaMgSi_2O_6$ | Insol. a. | 32052 |
| Hedenbergite | $CaFeSi_2O_6$ | Insol. HCl | (32080) |
| Augite | $(Ca, Mg)(Mg, Fe, Al)(Al, Si)_2O_6$ | Insol. a. | 30728 |
| Schefferite | $Ca(Mg, Fe, Mn)Si_2O_6$ | (Insol. a.) | |
| Jeffersonite | $Ca(Mg, Mn, Zn)Si_2O_6$ | (Insol. a.) | |
| (4) Acmite-Jadeite series $WYZ_2O_6$ | | | |
| Acmite | $NaFe(III)Si_2O_6$ | Very sl. sol. a. | |
| Jadeite | $NaAlSi_2O_6$ | Insol. a. | (33848) |
| Aegirite | $(Ca, Na)(Mg, Fe(III), Al)Si_2O_6$ | Insol. a. | |
| Spodumene | $LiAlSi_2O_6$ | Insol. a. | |
| (App.) | | | |
| Margarosanite | $(Pb, Ca, Mn)SiO_3$ | Gel. $HNO_3$ | |
| Babingtonite | $Ca_2Fe(II)Fe(III)Si_5O_{14}(OH)$ | Gel. HCl | |
| Taramellite | $BaFeSi_2O_6(OH)$ | Insol. a. | |
| Hyalotekite | $(Pb, Ca, Ba)_4BSi_6O_{17}(F, OH)$ | Insol. a. | |
| Neptunite | $Na_2FeTiSi_4O_{12}$ | Insol. HF | (33938) |

TABLE III. (Continued)

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| Calcium metasilicates | | | |
| Inesite | $Ca_2Mn_7H_2Si_{10}O_{30}\cdot 5H_2O$ | (Sol. HCl) | |
| Hillebrandite | $Ca_2SiO_4\cdot H_2O$ | Sol. HCl | (28027)*1) |
| Riversideite | $Ca_5H_2Si_6O_{18}\cdot 2H_2O$ | Sol. HCl | (31285) |
| Copper metasilicates | | | |
| Chrysocolla | $CuSiO_3\cdot nH_2O$ | Decomp. a. | |
| Shattuckite | $8CuSiO_3\cdot 4H_2O$ | (Decomp. a.) | |
| Plancheite | $14CuSiO_3\cdot 4H_2O$ | (Decomp. a.) | |
| The others | | | |
| Carpholite | $MnAl_2Si_2O_6(OH)_4$ | Insol. HCl | |
| Stokesite | $CaSnSi_3O_9\cdot 2H_2O$ | Insol. a. | |
| Searlesite | $NaBSi_2O_6\cdot H_2O$ | Decomp. HCl | |
| Bavenite | $Ca_4AlBe_3HSi_9O_{27}\cdot H_2O$ | (Sl. sol. a.) | |
| Cainosite | $Ca_2(Ce, Y)_2Si_4O_{12}CO_3\cdot 1\sim 2H_2O$ | Sol. HCl | |
| Epididymite | $NaBeSi_3O_7(OH)$ | Very sl. sol. a. | |
| Elpidite | $Na_2(Zr, Ti)Si_6O_{15}\cdot 3H_2O$ | (Sl. sol. a.) | |
| Leucosphenite | $Ba(Na, Ca)_4Ti_3BSi_8O_{27}$ | Decomp. HF | |
| Ussingite | $Na_2Al(Si_3O_8)(OH)$ | Gel. HCl | |
| Amphybole group $(W, X, Y)_{7\sim 8}(Z_4O_{11})_2(O, OH, F)_2$ | | | |
| (1) Anthophyllite series | | | |
| Anthophyllite | $(Mg, Fe)_7Si_8O_{22}(OH)_2$ | Insol. | |
| Gedrite | $(Mg, Fe, Al)_7(Al, Si)_8O_{22}(OH)_2$ | (Insol.) | |
| (2) Cummingtonite series $X_7(Z_4O_{11})_2(OH)_2$ | | | |
| Cummingtonite | $(Mg, Fe)_7Si_8O_{22}(OH)_2$ | (Insol.) | |
| Grunerite | $(Mg, Fe, Mn)_7Si_8O_{22}(OH)_2$ | Insol. a. | |
| Kupfferite | $Mg_7Si_8O_{22}(OH)_2$ | (Insol.) | (32430) |
| (3) Tremolite series | | | |
| Tremolite | $Ca_2Mg_5Si_8O_{22}(OH)_2$ | Insol. | 32284 |
| Actinolite | $Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$ | Insol. | |
| (4) Hornblende series $W_6(X, Y)_{10}(Z_4O_{11})_4(O, OH, F)_4$ | | | |
| Edenite | $Ca_4Na_2Mg_{10}Al_2Si_{14}O_{44}(OH, F)_4$ | (Insol.) | (31272)*2) |
| Pargasite | $Ca_4Na_2Mg_9Al_4Si_{13}O_{44}(OH, F)_4$ | (Insol.) | (31088)*3) |
| Hastingsite | $Ca_4Na_2Mg_8Al_6Si_{12}O_{44}(OH, F)_4$ | (Insol.) | (30904)*3) |
| Hornblende | $Ca_4Na_2(Mg, Fe(II))_8(Al, Fe(III), Ti)_6Si_{12}O_{44}(OH, O)_4$ | Insol. a. | |
| Kaersutite | $Ca_4Na(Mg, Fe(II))_7(Al, Fe(III))_6Ti_2Si_{12}O_{46}(OH)_2$ | (Insol.) | |
| Arfvedosonite | $Na_6Mg_8Al_2Si_{16}O_{44}(OH, F)_4$ | Insol. a. | (32538)*2) |
| 〃 | $Ca_2Na_4Fe(II)_7(Al, Fe(III))_6Si_{13}O_{44}(OH)_4$ | Insol. a. | |
| Holmquistite | $CaNaLi_2Mg_6Al_5Si_{15}O_{44}(OH)_2$ | (Insol. a.) | |
| Glaucophane | $Na_4Mg_6Al_4Si_{16}O_{44}(OH, F)_4$ | Insol. a. | (33182)*2) |
| Riebeckite | $Na_6Fe(II)_6Fe(III)_4Si_{16}O_{46}(OH)_2$ | Insol. a. | |
| Narsarsukite | $Na_2(Ti, Fe(III))Si_4(O, OH, F)_{11}$ | Insol. a. | |
| Chrysotile | $(Mg, Fe)_6Si_4O_{11}(OH)_6\cdot H_2O$ | Decomp. $H_2SO_4$ | (29468)*3) |
| (App.) | | | |
| Sepiolite | $Mg_8H_2(Si_4O_{11})_3\cdot 3H_2O$ | Decomp. HCl | (32627) |
| Attapulgite | $Mg_5Si_8O_{20}(OH)_2\cdot 8H_2O$ | (Decomp. a.) | (31076) |

*1) This value was calculated regarding the chemical formula of hillebrandite as $Ca_2SiO_3(OH)_2$.

*2) These values were calculated regarding ……(OH, F, or, OH, O)$_4$ as …… (OH)$_4$.

*3) This value was calculated regarding (Mg, Fe)$_6$…… as Mg$_6$…….

TABLE IV. REACTIVITY OF PHYLLOSILICATE MINERALS TOWARD ACIDS

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| | Phyllosilicates of aluminum. $Y_pSi_4O_{10}(OH)_{3p-4}\cdot sH_2O$ Y=Al, Fe(III), rarely Cr; $p=2\sim3$; $s=0\sim4$. | | |
| 2:1 Type | | | |
| Pyrophyllite | $Al_2Si_4O_{10}(OH)_2$ | Sl. decomp. HCl | 32558 |
| 1:1 Type kaolin minerals | $Al_4Si_4O_{10}(OH)_8$ | | |
| Kaolinite | $Al_4Si_4O_{10}(OH)_8$ | Sl. decomp. HCl | |
| Dickite | 〃 | (Sl. decomp. HCl) | 32165 |
| Nacrite | 〃 | (Sl. decomp. HCl) | |
| | Phyllosilicates of iron, magnesium, calcium and manganese. | | |
| 2:1 Type | | | |
| Talc | $Mg_3Si_4O_{10}(OH)_2$ | Undecomp. a. | (32516) |
| Minnesotaite | $(Fe(II), Mg)_{5.5}(Si, Al, Fe(III))_8O_{18.5}(OH)_{5.5}$ | (Undecomp. a.) | |
| Chlorite graup (abbr.) | | | |
| Clinochlore | (abbr.) | Decomp. $H_2SO_4$ | |
| Penninite | (abbr.) | Decomp. $H_2SO_4$ | |
| Prochlorite | (abbr.) | Decomp. hot $H_2SO_4$ | |
| Montmorillonite group | | | |
| Montmorillonite | (E. C.)*1)$_{0.67}(Al_{3.33}Mg_{0.67})Si_8O_{20}(OH)_4$ | Decomp. boiling a. | |
| Beidellite | (E. C.)*1)$_{0.67}Al_4(Si_{7.33}Al_{0.67})O_{20}(OH)_4$ | (Decomp. boiling a.) | |
| Nontronite | (E. C.)*1)$_{0.67}Fe_4(Si_{7.33}Al_{0.67})O_{20}(OH)_4$ | Gel. HCl | |
| Saponite | (E. C.)*1)$_{0.67}Mg_6(Si_{7.33}Al_{0.67})O_{20}(OH)_4$ | Decomp. $H_2SO_4$ | |
| Iron-saponite | (E. C.)*1)$_{0.67}(Mg, Fe)_6(Si_{7.33}Al_{0.67})O_{20}(OH)_4$ | (Decomp. a.) | |
| Sauconite | (E. C.)*1)$_{0.67}(Mg, Fe, Zn)_6(Si_{7.33}Al_{0.67})O_{20}(OH)_4$ | (Decomp. a.) | |
| Vermiculite group | | | |
| Vermiculite | $(Mg, Fe)_{2\sim3}(Si, Al, Fe(II))_4O_{10}(OH)_2\cdot 4H_2O$ | (Decomp. a.) | |
| Brittle mica group | | | |
| Chalcodite | $(Mg, Fe)_{13}Al_4Si_{18}O_{50}(OH)_{10}\cdot 10H_2O$ | (Decomp. a.) | |
| Epichlorite | $(Mg, Fe)_{10}Al_6Si_{18}O_{40}(OH)_{10}\cdot 8H_2O$ | (Decomp. a.) | |
| Stilpnomelane | $(K, Na, Ca)_{0\sim1}(Fe(II), Mg, Al, Fe(III))_{7\sim8}Si_8O_{22\sim24}(OH)_{2\sim4}\cdot H_2O$ | (Decomp. a.) | |
| Margarite | $CaAl_2(Al_2Si_2)O_{10}(OH)_2$ | Sl. decomp. HCl | (30914) |
| Prehnite | $Ca_2Al_2Si_3O_{10}(OH)_2$ | Sl. decomp. HCl | (31496) |
| Chloritoid | $(Fe, Mg)_2Al_4Si_2O_{10}(OH)_4$ | Decomp. $H_2SO_4$ | (29976)*2) |
| Clintonite | $X_4Z_4O_{10}(OH)_2$ X=Mg : Ca : Al=3 : 2 : 1, Al : Si=2 : 1. | Decomp. hot & conc. a. | |
| Xanthophyllite | $(Mg, Ca, Al)_4(Si, Al)_4O_{10}(OH)_2$ | (Decomp. a.) | |
| Mica group | | | |
| (1) Muscovite series | | | |
| Muscovite | $KAl_2(AlSi_3)O_{10}(OH, F)_2$ | Insol. | 32494 |
| Phengite | $K_4Mg_2Al_8Si_{14}O_{40}(OH)_8$ | Insol. | (32858) |
| Alurgite | $K_4Mg_3Al_7Si_{14}O_{39}(OH)_9$ | (Insol.) | |
| Paragonite | $Na_4Al_{12}Si_{12}O_{40}(OH)_8$ | Insol. HCl | (32540) |
| Roscoelite | $K_4V_8Al_4Si_{12}O_{40}(OH)_8$ | Sl. decomp. $H_2SO_4$ | |
| (2) Biotite series | | | |
| Biotite | $K_4(Mg, Fe)_{12}Al_4Si_{12}O_{40}(OH)_8$ | Decomp. $H_2SO_4$ | 30475 |
| Phlogopite | $K_4Mg_{12}Al_4Si_{12}O_{40}(OH)_8$ | Decomp. $H_2SO_4$ | (30454) |
| Cryophyllite | $K_4Mg_{10}Al_8Si_{10}O_{40}(OH)_8$ | (Decomp. $H_2SO_4$) | (30090) |
| (3) Lepidolite series | | | |
| Lepidolite | $K_4Mg_4Li_4Al_8Si_{12}O_{40}(OH)_4F_4$ | Very sl. sol. HCl | |
| 〃 | $K_4Li_6Al_8Si_{14}O_{42}(OH)_4F_2$ | ( 〃 ) | |
| 〃 | $K_4Li_6Al_7Si_{14}O_{39}(OH)_2F_7$ | ( 〃 ) | |
| Zinnwaldite | $K_4Fe(II)_4Li_4Al_8Si_{12}O_{40}(OH)_4F_4$ | Sl. sol. HCl | |
| Polylithionite | $K_4Li_8Al_4Si_{16}O_{40}F_8$ | (Sl. sol. HCl) | |

TABLE IV. (Continued)

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| (Misc.) | | | |
| Glauconite | $K_{2\sim3}(Mg, Fe, Ca)_{1\sim3}(Fe(III), Al)_{3\sim6}(Si_{13\sim14}Al_{2\sim3})O_{38\sim40}(OH)_{6\sim10}$ | Decomp. HCl | |
| (App.) | | | |
| Pholiodolite | $KMg_6AlSi_7O_{20}(OH)_4 \cdot 3H_2O$ | (Decomp. HCl) | (30733) |
| Cookeite | $(Li, Al)_4(Si, Al)_4O_{10}(OH)_4 \cdot 2H_2O$ | Decomp. $H_2SO_4$ | |
| Bityite | $CaLiAl_3BeSi_2O_{10}(OH)_2$ | (Insol.) | |
| Ganophyllite | $NaMn_6Al_2(Si_4O_{10})_2(OH)_{11}$ (?) | (Decomp. a.) | |
| 1 : 1 Type | | | |
| Antigorite | $Mg_6Si_4O_{10}(OH)_8$ | Decomp. $H_2SO_4$ | (29445) |
| Greenalite | $(Fe(II), Mg)_9Fe(III)_2Si_8O_{22}(OH)_{12} \cdot 2H_2O$ | (Decomp. $H_2SO_4$) | |
| Neponite | $(Mg, Ni)_6Si_4O_{10}(OH)_8$ | (Decomp. $H_2SO_4$) | |
| Connarite | $(Ni, Mg)_8(Si_4O_{10})_3(OH)_4 \cdot 6H_2O$ | (Decomp. $H_2SO_4$) | |
| Amesite | $(Mg, Al, Fe(II))_3(Si, Al)_2O_5(OH)_4$ | (Decomp. $H_2SO_4$) | |
| Cronstedite | $(Mg, Ca, Fe(II), Fe(III), Al)_{3\sim4}(Si, Al)_2O_5(OH)_4$ | (Decomp. $H_2SO_4$) | |
| Chamosite | $(Al, Fe(II), Fe(III), Mg, Ti)_3(Si, Al)_2O_5(OH)_4$ | (Decomp. $H_2SO_4$) | |
| (App.) | | | |
| Zeophyllite | $Ca_8Si_6O_{15}(OH, F)_{10}$ | (Decomp. HCl, $HNO_3$) | (29376)*3) |
| Friedelite | $Mn_8Si_6O_{15}(OH, Cl)_{10}$ | Gel. HCl | |
| Pyrosmalite | $(Mn, Fe)_8Si_6O_{15}(OH, Cl)_{10}$ | Gel. HCl | |
| Schallerite | $Mn_8(Si, Al)_6O_{15}(OH, Cl)_{10}$ | (Gel. HCl) | |
| Ferroschallerite | $(Fe, Mn)_8(Si, Al)_6O_{15}(OH, Cl)_{10}$ | (Gel. HCl) | |
| Centrallasite | $Ca_4Si_6O_{15}(OH)_2 \cdot 5H_2O$ | Decomp. HCl | (30844) |
| Truscottite | $(Ca, Mg)_4Si_6O_{15}(OH)_2 \cdot 5H_2O$ | (Decomp. HCl) | |
| Gyrolite | $Ca_4Si_6O_{15}(OH)_2 \cdot 3H_2O$ (?) | (Decomp. HCl, $HNO_3$) | (31457) (?) |
| Bementite | $Mn_5Si_4O_{10}(OH)_6$ | Gel. hot HCl | |
| Errite | $Mn_4Si_4O_{10}(OH)_4 \cdot 3H_2O$ | (Gel. a.) | |
| Apophyllite | $KCa_4(Si_4O_{10})_2F \cdot 8H_2O$ | Decomp. a. | |
| Okenite | $Ca_2(Si_4O_{10}) \cdot 4H_2O$ | Gel. HCl | (31354) |
| | Anhydrous phyllosilicates containing no aluminum. | | |
| Gillespite | $BaFeSi_4O_{10}$ | (Decomp. HCl, $HNO_3$) | |
| Sanbornite | $Ba_2Si_4O_{10}$ | (Decomp. HCl, $HNO_3$) | |

*1) E. C. = Exchangeable cations (Na, K, Ca, etc.)
*2) This value was calculated regarding the chemical formula of chloritoid as $Fe_2Al_4Si_2O_{10}(OH)_4$.
*3) This value was calculated regarding ……$(OH, F)_{10}$ as ……$(OH)_{10}$.

TABLE V. REACTIVITY OF TECTOSILICATE MINERALS TOWARD ACIDS

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| | W=Ca, Na, K; Li, Cs(rare); Mn, Fe, Zn(very rare) | | |
| | Z=Si, Al; Be(rare); N=S, Cl, $CO_3$, $SO_4$, $H_2O$ | | |
| Silica group | | | |
| Quartz | $SiO_2$ | Insol. | 37320 |
| Petalite group | | | |
| Petalite | $(Li, Na)AlSi_4O_{10}$ | Insol. | |
| Milarite | $KCa_2AlBe_2Si_{12}O_{30} \cdot \frac{1}{2}H_2O$ | Insol. | |
| Leifite | $Na_4Al_2Si_9O_{22}F_2$ | (Insol.) | |
| Feldspar group $WZ_4O_8$, W=Na, Ca, K, Ba; Z=Si, Al; Si : Al=3 : 1∼1 | | | |
| (1) Monoclinic system | | | |
| Orthoclase | $KAlSi_3O_8$ | Insol. | 34266 |
| Soda orthoclase | $(K, Na)AlSi_3O_8$ | Insol. | |
| Hyalophane | $(K, Na, Ba)Al(Al, Si)Si_2O_8$ | Insol. | |
| Celsian | $BaAl_2Si_2O_8$ | Sol. HCl | |

TABLE V. (Continued)

| Minerals | Chemical formula | Reactivity toward acids | Bonding energy (kcal.) |
|---|---|---|---|
| (2) Triclinic system | | | |
| (a) Microcline series :— | | | |
| Microcline | $KAlSi_3O_8$ | Insol. | (34521) |
| Soda microcline | $(K, Na)AlSi_3O_8$ | (Insol.) | |
| Anorthoclase | $(Na, K)AlSi_3O_8$ | Insol. | |
| (b) Plagioclase series :— | | | |
| Albite | $NaAlSi_3O_8$ | Insol. | 34335 |
| Anorthite | $CaAl_2Si_2O_8$ | Decomp. HCl | 31935 |
| Leucite | $KAlSi_2O_6$ | Decomp. HCl | (33248) |
| Nepheline group $WZ_2O_4$ | | | |
| Nepheline | $KNa_3(AlSiO_4)_4$ | Gel. a. | (31465) |
| Kaliophyllite | $KAlSiO_4$ | Gel. a. | (31212) |
| β-Eucryptite | β-$LiAlSiO_4$ | Gel. HCl | |
| Cancrinite group | | | |
| Cancrinite | $(Na, K)_6Ca_2(SO_4)_2(AlSiO_4)_6$ | Sol. HCl | |
| Davyne | $(Na_2, Ca)_4(CO_3)(H_2O)_{0\sim3}(AlSiO_4)_6$ | Gel. HCl | |
| Sodalite group | | | |
| Sodalite | $Na_8Al_6Si_6O_{24}Cl_2$ | Sol. HCl | |
| Noselite | $Na_6(AlSiO_4)_6\cdot Na_2SO_4$ | Gel. HCl | |
| Hauyne | $(Na, Ca)_{8\sim4}(SO_4)_{2\sim1}(AlSiO_4)_6$ | Sol. HCl | |
| Helvite | $Mn_8S_2(BeSiO_4)_6$ | Sol. HCl | |
| Danalite | $Fe_8S_2(BeSiO_4)_6$ | Gel. HCl | |
| Scapolite series $W_4Z_{12}O_{24}N$ | | | |
| Marialite | $(Na, Ca)_4Al_3(Al, Si)_3Si_6O_{24}(Cl, CO_3, SO_4)$ | Sl. decomp. HCl | |
| Meionite | $(Ca, Na)_4Al_3(Al, Si)_3Si_6O_{24}(Cl, CO_3, SO_4)$ | Decomp. HCl | |
| Zeolite group | | | |
| Mordenite | $(Ca, K_2, Na_2)Al_2Si_{10}O_{24}\cdot 7H_2O$ | Decomp. a. | (32590) |
| Heulandite group | | | |
| Clinoptilolite | $Ca_2Na_3Al_7Si_{33}O_{80}\cdot 23H_2O$ (?) | Decomp. a. | (32974) (?) |
| Heulandite | $CaAl_2Si_7O_{18}\cdot 6H_2O$ | Decomp. a. | (32375) |
| Epistilbite | $CaAl_2Si_6O_{16}\cdot 5H_2O$ | Decomp. HCl | (32268) |
| Brewsterite | $(Sr, Ba, Ca)Al_2Si_6O_{16}\cdot 5H_2O$ | Decomp. HCl | |
| Desmine group | | | |
| Desmine | $CaAl_2Si_7O_{18}\cdot 7H_2O$ | Decomp. HCl | (32069) |
| Harmotome | $BaAl_2Si_6O_{16}\cdot 6H_2O$ | Decomp. HCl | |
| Phillipsite | $KCaAl_3Si_5O_{16}\cdot 6H_2O$ | Gel. HCl | (30815) |
| Gismondite | $CaAl_2Si_2O_8\cdot 4H_2O$ | Gel. HCl | (29530) |
| Erionite | $(K_2, Na_2, Ca)Al_2Si_6O_{16}\cdot 6H_2O$ (?) | Sol. HCl | |
| Chabazite group | | | |
| Chabazite | $(Ca, Na_2)Al_2Si_4O_{12}\cdot 6H_2O$ | Decomp. HCl | |
| Gmelinite | $(Na_2, Ca)Al_2Si_4O_{12}\cdot 6H_2O$ | Decomp. HCl | |
| Levynite | $CaAl_2Si_4O_{12}\cdot 6H_2O$ | Gel. a. | (30727) |
| Thomsonite group | | | |
| Thomsonite | $NaCa_2[Al_4(Al, Si)_2Si_4]O_{20}\cdot 5H_2O$ | Gel. HCl | |
| Gonnardite | $(Ca, Na)_3(Al, Si)_{10}O_{20}\cdot 6H_2O$ | (Gel. HCl) | |
| Ashcroffine | $KNa(Ca, Mg, Mn)Al_4Si_5O_{18}\cdot 8H_2O$ | (Gel. HCl) | |
| Natrolite group | | | |
| Natrolite | $Na_2Al_2Si_3O_{10}\cdot 2H_2O$ | Gel. a. | (31240) |
| Mesolite | $Na_2Ca_2Al_6Si_9O_{30}\cdot 8H_2O$ | Gel. a. | (31143) |
| Scolesite | $CaAl_2Si_3O_{10}\cdot 3H_2O$ | Gel. a. | (31098) |
| Edingtonite | $BaAl_2Si_3O_{10}\cdot 3H_2O$ | Gel. a. | |
| Unassigned | | | |
| Yugawaralite | $Ca_4Al_7Si_{20}O_{54}\cdot 14H_2O$ | (Gel. a.) | (32657) |
| Analcite | $NaAlSi_2O_6\cdot H_2O$ | Gel. HCl | (32109) |
| Faujasite | $CaNa_2Al_4Si_8O_{24}\cdot 16H_2O$ | Decomp. HCl | (30009) |
| Laumonite | $CaAl_2Si_4O_{12}\cdot 4H_2O$ | Gel. HCl | (31478) |
| Ferrierite | $(Na, K)_2MgAl_3Si_{15}O_{36}(OH)\cdot 9H_2O$ | (Gel. HCl) | |
| Questionable | | | |
| Didymolite | $(Ca, Mg, Fe)Al_2Si_3O_{10}$ | Insol. a. | |
| D'Achiardite | $(K, Na)CaH_3Al_2Si_9O_{24}\cdot 6H_2O$ | Decomp. HCl | |

trimerite contains Be, it is dissolved by hydrochloric acid. This fact may be due to the presence of a considerable amount of electropositive Mn(II) and Ca.

Generally, it may safely be assumed that 1) of the above-mentioned requirements and the singularity of the above eight metallic elements hold in the case of nesosilicates.

Furthermore, it is noteworthy that the nesosilicate minerals containing Ca, Sr, Ba and Pb react with difficulty with sulfuric acid, because sulfates of these metals are hardly soluble. Of these metals, lead chloride is soluble with difficulty in water, and so the silicate minerals containing Pb do not react easily with hydrochloric acid at ordinary temperatures.

**Sorosilicate Minerals.**—The results for the solosilicate minerals are listed in Table II. The above inductive rules appear also to be applicable in this case as well as in the case of the nesosilicate minerals. For example, osumilite, indialite, cordierite, the tourmaline and the epidote series minerals may be scarcely attacked by acids, because of the presence of great amounts of Al, and Fe(III); and then for the same reason, schorl probably appears to be undecomposed by acids. In the thalenite group minerals, the fact that thortveiteit is insoluble in acids, in spite of the reactivity of cerite toward acids, is presumably due to the existence of scandium atoms having comparatively large values of $\phi$, $\phi'$ or F. S. Similarly, the fact that bertrandite only in the hemimorphite group is undecomposed by acids appears to be due to the presence of Be. Beryl containing Al and Be is insoluble as shown from the above results. In addition, in the melilite series, leucophanite and meliphanite are slightly decomposed by hydrochloric acid (and perhaps nitric acid) owing to the existence of Be.

From this standpoint, it appears to be deducted that thalenite and rowlandite are probably attacked by acids. Moreover, it is noteworthy that dioptase ($Cu_6Si_6O_{18}\cdot 6H_2O$) having the structure identical with that of beryl[9] is easily decomposed by acids, because $Cu^{2+}$ has remarkably smaller $\phi$, $\phi'$ or F. S. than those of $Be^{2+}$. But the unreactivity of the rhodonite series[10] seems to be impossible to explain from this viewpoint, and appears to indicate the necessity of consideration for their structures, but now no satisfactory explanation has been offered as to this fact.

**Inosilicate Minerals.**—As is generally known, the inosilicate minerals are structurally classified in the pyroxene and the amphybole group. The former consists in structure with infinite single chain $(SiO_3)^{2-}_{\infty}$ of $(SiO_4)^{4-}$ tetrahedra with common corners, and the latter is characterized by the double chains of the type $(Si_4O_{11})^{6-}_{\infty}$.

The results are listed in Table III.

From Table III, it would be presumably derived that these inosilicate minerals could not for the most part be decomposed by acids. Taken in connection with their structures, this fact would seem to prove that these silicates are probably constructed by the compact arrangements of metallic ions and $(SiO_3)^{2-}_{\infty}$ or $(Si_4O_{11})^{-6}_{\infty}$ ions; in other words, their metal ions are compactly surrounded with the above-cited giant ions. Relating to this structure, it is noteworthy that the inosilicates containing alkali metals, e. g., the acmite-jadeite series and hornblende series, are not decomposed by acids. Therefore, it seems that the structural factor adds a striking effect to the reactivity toward acids in these cases. But the chemical composition of these silicates also has a comparative effect on their reactivity. For example, the inertness of the above-mentioned acmite-jadeite series and epididymite are probably in part due to the existence of Be and Al; and from the same viewpoint, it is presumably best to deduct the inertness of carpholite and bavenite. Furthermore, the fact that sepiolite and attapulgite are easily decomposed by acids would probably be due to the existence of large voids such as caves passing through between chains of $(Si_4O_{11})^{6-}_{\infty}$ ions[11].

**Phyllosilicate Minerals.** — As stated above, it is confirmed from the Table IV that all the 1:1 type phyllosilicate minerals are easily decomposed by acids, except the aluminum ones (e. g., the kaolin minerals) as was expected. On the contrary, in the 2:1 type phyllosilicate minerals, the magnesium type (talc) also is unattacked by acids, as well as the aluminum type (pyrophyllite). This seems to be mainly due to its 2:1 type structure; namely, all the magnesium ions in talc are compactly sandwiched with the two infinite layerous ions $(Si_2O_5)^{2-}_{\infty}$. Furthermore, the inertness of the muscovite and lepidolite series appears to be in part due to the above-cited structure and in part to the existence of aluminum. The biotite series contain no aluminum for positive ions, and then these would perhaps be attacked by acids.

**Tectosilicate Minerals.** — Table V seems to indicate that the reactivity of tectosilicate minerals toward acids are scarcely connected

9) N. V. Belov, *Compt. Rend. Acad. Sci. Russ.* **37**, 139 (1942).

10) E. H. Kraus, W. F. Hunt and L. S. Ramsdell, "Mineralogy, An Introduction to the Study of Minerals and Crystals", 3rd. Ed., McGraw-Hill Book Co., Inc., New York and London (1936), p. 368.

11) W. T. Grandquist and R. C. Amero, *J. Am. Chem. Soc.*, **70**, 3265 (1948).

with their chemical compositions. For example, the fact that orthoclase, microclire, and albite are insoluble to acids, and leucite and nepheline are decomposed by acids, cannot be explained from their chemical compositions. Therefore, in this case, it is suggested that their structures have an important effect on their reactivity.

As for their structures, the position and state of metallic ions in their crystal lattices would seem to carry on connection with their reactivity.

### Results from the Bonding Energies

It appears that the bonding energies of the silicate minerals are closely related to their reactivity. Especially the bonding energies of the tectosilicate minerals would seem to be important. As for this problem, Keller[12] made a computation by adding the energies of the bonds between their constituent cations and oxygen, starting with the elements in the gaseous state, on the basis of the data from Huggins and Sun[13].

The author computed the bonding energies of the various silicate minerals by adding the bonding energies of their constituent elements, utilizing data compiled by Huggins and Sun[13], and Keller[12]. Of the valuse in Tables I—V, those in parentheses are computed by the author, and the rest are reprinted from Keller's paper.

It is reasonable to assume that there are some deep relationships between the reactivity and the bonding energies of silicate minerals. Judging from the comparison of these two properties in Tables I—V, the following results were obtained. Generally speaking, the neso-, soro-, ino-, and phyllo-silicate minerals of which bonding energies are less than about 30500 kcal. and the tectosilicate minerals of which these energies are less than about 33500 kcal. seem to be decomposed by acids. The fact that the tectosilicate minerals alone are in particular different from others appears presumably to be relative to the singularity of themselves; namely, this seems to depend primarily upon their ultimately polymerized structures—the three-dimentional frameworks —constructed by complete sharing of all oxygens in all the tetrahedra contained in their structures.

12) W. D. Keller, *Am. Mineralogist*, **39**, 783 (1954).

13) M. L. Huggins and K-H. Sun, *J. Phys. Chem.*, **50**, 319 (1946).

### Summary

In this paper, the author proposed a classified table of metals contained in silicate minerals, and the qualitative and conventional rules in which it appeared possible to predict the reactivity of all the known silicate minerals toward ordinary mineral acids. In the classification and rules, ionic potential, Goldschmidt's polarizing power, and field strength of the metals in the silicate minerals play important roles.

The rules are summarized as follows: 1) the silicate minerals—especially, the neso- and soro-silicate ones composed of the comparative simple ionic crystal lattices—containing the less electropositive metals (e. g., Ti, Be, Al, Cr, V(III), Fe(III), Mn(III), Zr, etc.) are generally unattacked by acids; 2) in the ino-, phyllo-, and tecto-silicate minerals, which contain various polymerized and giant silicate ions, their structures exert a favorable influence upon their reactivity toward acids. Thus, in these minerals, it is necessary for us to take their structural effects into consideration, besides the above rule 1); and 3) the bonding energies of silicate minerals are closely related to their reactivity. In general, the neso-, soro-, ino-, and phyllo-silicate minerals of which bonding energies are less than about 30500 kcal. and the tectosilicate ones of which the energies are less than about 33500 kcal. seem to be decomposed by acids.

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