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Bibliography and Index of Conodonts, 1959-1963[1]

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ABSTRACT.—330 articles pertaining to conodonts published during 1959-1963, and 30 articles published prior to 1959, are listed and indexed. The articles contain descriptions of 264 new forms, including 209 new species and 29 new genera. In addition to the index of new forms, a stratigraphic-geographic index of conodont-bearing formations is included which shows that conodonts are now known to range from Middle Cambrian through Late Triassic time.

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INTRODUCTION

This is the second in a series of conodont bibliographies and indexes which has been compiled as a supplement to Fay's Catalogue of conodonts. The first one covered the period 1949-1958 (Ash, 1961), and this covers the years 1959-1963. Both have been compared with Ellison's two conodont bibliographies (1962b and 1963) and significant omissions have been added to this one.

The author is indebted to the students of conodonts who have generously sent him reprints for use in this compilation. He is particularly indebted to Dr. John Huddle, Dr. Willi Ziegler, Mr. Dwayne D. Stone, Mrs. Elizabeth Kuntz, and Mrs. Mary Paul who have been of assistance to him in various ways.

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Listed in the following bibliography are the 330 articles which are known to have been published during the calendar years 1959-1962 and most of 1963, and 30 articles that were published prior to 1959. An asterisk (*) marks those articles in which new forms of conodonts are proposed and those which are of taxonomic interest for other reasons.

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[1]Publication authorized by the Director; U.S. Geological Survey

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INDEX OF NEW CONODONTS

All of the new forms of conodonts proposed in the articles cited in the bibliographic section of this paper are listed here. Included in the alphabetically arranged list are: 7 new subfamilies, 29 new genera, 4 new subgenera, 209 new species, 18 new subspecies, and 4 new varieties of disjunct units (form genera of some authors). No new conodont assemblages were described in any of the cited articles.

The order of items given in each generic and subgeneric entry is as follows: Name of the genus or subgenus, its author, date of publication, and number of the page on which the new form is described; name of the type species, its author, date of publication; and the geologic age of the new form. If the type species is not listed in this index the full reference can be found in either Fay's Catalogue of conodonts or in my Bibliography and index of conodonts for the period 1949-1958.

The order of items given in each species, subspecies, and variety entry is as follows: Name of the new form, its author, date of its publication, page number on which it is described, and numbers of the illustrations in which it is figured; its geologic age, and the general geographical area from which it was collected.

Acodus inornatus Ethington, 1959, p. 268, pl. 39, fig. 11. Late Ordovician, Iowa.
Acontiodus cooperi Sweet and Bergström, 1962, pp. 1221-1222, pl. 168, figs. 2, 3; text-fig. 1G. Middle Ordovician, Alabama.
A. falcatus Ethington, 1959, pp. 268-269, pl. 39, figs. 6-7. Late Orodvician, Iowa.
Ambalodus planus Sergeeva, 1963, pp. 105-106, pl. 8, figs. 11-14, text-fig. 10. Early Ordovician, Russia.
A. triangularis erratious Bergström, 1961, pp. 26-27, pl. 3, figs. 15-17. Middle Ordovician Sweden.
A. t. suecicus Bergström, 1961, pp. 28-19, pl. 3, figs. 11-14. Middle Ordovician, Sweden.
Amorphognathus elongata Bergström, 1961, pp. 31-32, pl. 5, figs. 1-3. Middle Ordovician, Sweden.
A. ordovicica simplicior Bergström, 1961, pp. 34-35, pl. 4, figs. 2, 5, 6. Middle Ordovician, Sweden.
A. tvaerensis Bergström, 1961, pp. 36-37, pl. 4. figs, 7-10. Middle Ordovician, Sweden.
A. variabilis Sergeeva, 1962, pp.106-107, pl. 8, figs. 15-17, text-fig. 11. Early Ordovician, Russia.
Ancyrognathus crypa Ziegler, 1962b, pp. 49-50, pl. 9, figs. 2-6. Late Devonian, Germany.
ANCYROLEPIS Ziegler, 1959b, pp. 77-78. *Ancyrolepis cruciformis* Ziegler, 1959a. Late Devonian.
A. cruciformis Ziegler, 1959a, pp. 78-80, pl. 7, figs. 1-4. Late Devonian, Germany.
Apatognathus tribulosus Clark and Ethington, 1962, p. 107, pl. 1, figs. 3, 7, 13, 17. Early Permain, Texas, Wyoming.
Aphelognathus irregularis Pulse and Sweet, 1960, pp. 249-250, pl. 36, figs. 15, 17. Late Ordovician, Indiana, Kentucky, and Ohio.
Bactrognathus communis Hass, 1959a, pp. 380-381, pl. 46, figs. 20, 25-27, 30, 31. Early Mississippian, Texas.
B. penehamata Hass, 1959a, p. 381, pl. 46, figs. 22, 23, 29. Early Mississippian, Texas.
BALOGNATHINAE Hass, 1959a, p. 379. A new subfamily which includes the following genera: *Balognathus* Rhodes, and *Icriodella* Rhodes.
BELODINA Ethington, 1959, pp. 271-272. *Belodus grandis* Stauffer, 1935. Middle and Late Ordovician.
B. alabamenis Sweet and Bergström, 1962, pp. 1223-1224, pl. 170, figs. 10, 11. Middle Ordovician, Alabama.
B. dartoni Stone and Furnish; 1959, p. 220, pl. 31, fig. 15. Late Ordovician, Wyoming.
B. kirki Stone and Furnish, 1959, p. 221, pl. 31, figs. 12-13. Late Ordovician, Wyoming.
B. leithi Ethington and Furnish, 1960, pp. 269-270, pl. 38, fig. 12. Late Ordovician, Manitoba.
BRANMEHLA Hass, 1959a, p. 381. *Spathodus inornata* Branson and Mehl, 1934. Late Devonian and Early Mississippian.
Cavusgnathus inflexa Clarke, 1960, p. 23, pl. 3, figs. 18-19. Late Mississippian, Scotland.
CHIRODELLA Hirschmann, 1959, p. 71. *Metalonchodina triquetra* Tatge, 1956. Triassic.
COELOCERODONTUS Ethington, 1959, p. 273. *Coelocerodontus trigonius* Ethington, 1959. Late Ordovician.
C. digonius Sweet and Bergström, 1962. p. 1224, pl. 168, fig. 1; text-fig. 1F. Middle Ordovician, Alabama.
C. tetragonius Ethington, 1959, p. 273, pl. 39, fig. 15. Late Ordovician, Iowa.
C. trigonius Ethington, 1959, p. 273, pl. 39, fig. 14. Late Ordovician, Iowa.
Cordylodus excavatus Sweet, Turco, Warner and Wilkie, 1959, pp. 1045-1046, pl. 132, fig. 16. Late Ordovician, Ohio.
C. oklahomensis Müller, 1959c, pp. 447-448, pl. 15, figs. 15-16, text-fig. 3A. Late Cambrian, Oklahoma.
C. proavus Müller, 1959c, pp. 448-449, pl. 15, figs. 11-12, 18, text-fig. 3B. Late Cambrian Oklahoma.
C. robustus Ethington and Furnish, 1959, p. 543, pl. 73, fig. 11. Late Ordovician, Manitoba.
CORNUDINA Hirschmann, 1959, p. 44. *Ozarkodina breviramulis* Tatge, 1956. Triassic.
Ctenognathus pseudofissilis Lindström, 1959, p. 439, pl. 4, figs. 1-9. Middle and Late Ordovician, England.
CYRTONIODONTINAE Hass, 1959a, p. 378. A new subfamily which includes the following genera: *Cyrtoniodus* Stauffer, *Plectodina* Stauffer, *Gothodus* Lindström, *Paracordylodus* Lindström, *Holodontus* Rhodes, *Keislognathus* Rhodes, *Phragmodus* Branson and Mehl, *Zygognathus* Branson and Mehl, *Periodon* Hadding.

Cyrtoniodus sinclairi Ethington and Furnish, 1960, pp. 270-271, pl. 38, fig. 16. Late Ordovician, Manitoba.
Distacodus (?) cambricus Müller, 1959c, p. 450, pl. 14, figs. 1-2. Late Cambrian, Sweden.
D. palmeri Müller, 1959c, pp. 449-450, pl. 14, figs. 3-4. Late Cambrian, Nevada.
D. procerus Ethington, 1959, p. 275, pl. 39, fig. 8. Late Ordovician, Iowa.
DOLLYMAE Hass, 1959a, p. 394. *Dollymae sagittula* Hass, 1959a. Early Mississippian.
D. sagittula Hass, 1959a, p. 394, pl. 47, figs. 7, 10. Early Mississippian, Texas.
D. hassi Voges, 1959b, pp. 275-276, pl. 33, figs. 5-10. Early Mississippian, Germany.
EOBELODINA Sweet, Turco, Warner, and Wilkie, 1959, p. 1050. *Oistodus fornicalus* Stauffer, 1935. Middle and Late Ordovician.
EOFALODUS Harris, 1962, pp. 204-205. *Eofalodus brevis* Harris, 1962. Middle Ordovician.
E. brevis Harris, 1962, pp. 205-206, pl. 1, figs. 7a-7d. Middle Ordovician, Oklahoma.
Eoligonodina fairmountensis Pulse and Sweet, 1960, pp. 253-254, pl. 35, fig. 17. Late Ordovician, Kentucky.
E. magna Ethington, 1959, p. 277, pl. 40, figs. 3-4. Late Ordovician, Iowa.
E. ulrichi Stone and Furnish, 1959, pp. 222-223, pl. 32, figs. 16-18. Late Ordovician, Wyoming.
Euprioniodina glencartensis Clarke, 1960, pp. 5-6, pl. 1, fig. 5. Late Mississippian, Scotland.
Falcodus (?) alatoides Rexroad and Burton, 1961, pp. 1152-1153, pl. 140, fig. 8. Late Mississippian, Illinois.
F. parvidentatus Sergeeva, 1963, pp. 103-104, pl. 8 figs. 407, text-fig. 8, Early Ordovician, Russia.
F. simplex Sergeeva, 1963, pp. 104-105, pl. 8, figs. 8-10, text-fig. 9. Early Ordovician, Russia.
FURNISHINA Müller, 1959c, p. 451. *Furnishina furnishi* Müller, 1959c. Late Cambrian.
F. asymmetrica Müller, 1959c, pp. 451-452, pl. 11, figs. 16, 19. Late Cambrian, Germany.
F. bicarinata Müller, 1959c, p. 452, pl. 12, fig. 3. Late Cambrian, Wyoming.
F. furnishi Müller, 1959c, pp. 452-453, pl. 11, figs. 5, 6, 8, 9, 11-15, 17, 18, pl. 12, figs. 1, 6, text-figs. 6D-6E. Late Cambrian, Wyoming.
F. primitiva Müller, 1959c, p. 453, pl. 11, figs. 1-4. Late Cambrain, Germany.
F. quadrata Müller, 1959c, pp. 453-454, pl. 12, figs. 2, 4, 9, text-fig. 6C. Late Cambrian, Germany.
FURNISHIUS Clark, 1959, pp. 310-311, *Furnishius triserratus* Clark, 1959. Early Triassic.
F. triserratus Clark, 1959, p. 311, pl. 44, figs. 1-6. Early Triassic, Nevada.
Geniculatus glottoides Voges, 1959b, pp. 279-280, pl. 33, figs. 21-25. Early Mississippian, Germany.
GLADIGONDOLELLA Müller, 1962a, p. 116. *Polygnathus tethydis* Huckriede, 1958. Triassic, Upper Cretaceous (?).
Gnathodus clavatus Clarke, 1960, p. 25, pl. 4, figs. 4-9. Late Mississippian, Scotland.
G. commutatus var. *multinodosus* Higgins, 1962, pp. 8-9, pl. 2, figs. 13-18. Late Mississippian, Spain.
G. cruciformis Clarke, 1960, pp. 25-26, pl. 4, figs. 10-12. Late Mississippian, Scotland.
G. smithi Clarke, 1960, pp. 26-27, pl. 4, figs, 13-14; pl. 5, figs. 9-10. Late Mississippian, Scotland.
G. (Harltonodus) Elias, 1959, pp. 144-145. Mississippian, Texas.
G. (H.) bilineatus Elias, 1959, pp. 145-146, pl. 1, figs. 3-12. Early Mississippian, Texas.
G. (H.) bransoni Elias, 1959, pp. 147-148, pl. 1, figs. 13-18. Late Mississippian, Oklahoma.
G. (H.) minutus Elias, 1959, pp. 148-149, pl. 1, figs 22-25. Late Mississippian, Oklahoma.
Gondolella carinata Clark, 1959, pp. 308-309, pl. 44, figs. 15-19. Early Triassic Nevada.
G. gracilis Clark and Ethington, 1962, pp. 107-108, pl. 1, fig. 12; pl. 2, figs. 6, 10. Early Permian, Wyoming.
G. nankingensis Ching, 1960, pp. 238-246, pl. 2, figs. 5-8. Early Permian, China.
G. nevadensis Clark, 1959, p. 308, pl. 44, figs. 11-14. Early Triassic, Nevada.
G. planata Clark, 1959, p. 309, pl. 44, figs. 8-10. Early Triassic.
G. serrata Clark and Ethington, 1962, pp. 108-109, pl. 1, figs. 10-11, 15, 19; pl. 2, figs. 1, 5, 8-9, 11-14.
GONIODONTUS Ethington, 1959, p. 278. *Goniodontus superbus* Ethington, 1959. Late Ordovician.
G. superbus Ethington, 1959, p. 278, pl. 40, figs. 1-2. Late Ordovician, Iowa.

HADDINGODUS Sweet and Bergström, 1962, p. 1228. *Arabellites serra* Hadding, 1913. Middle Ordovician.
HERTZINA Müller, 1959c, p. 454. *Hertzina americana* Müller, 1959c. Late Cambrian.
H. americana Müller, 1959c, p. 455, pl. 13, figs. 25-26. Late Cambrian, Nevada.
H. (?) *bisulcata* Müller, 1959c, p. 456, pl. 13, figs. 22-24, 27. Late Cambrian, Sweden.
H. elongata Müller, 1959c, pp. 455-456, pl. 13, fig. 28. Late Cambrian, Germany.
Hibbardella fragilis Higgins, 1961, pp. 213-214, pl. 12, fig. 4, text-fig. 2. Late Mississippian, England.
H. pennata Higgins, 1961, p. 213, pl. 12, figs. 5-6. Late Mississippian, England.
Hindeodella dimitrovi Spasov and Ganev, 1960, pp. 82, 92, 94, pl. 2, fig. 1. Late Triassic, Bulgaria.
H. fragilis Hass, 1959a, p. 383, pl. 48, figs. 18, 21, 26. Early Mississippian, Texas.
H. mülleri Clark, 1959, p. 310, pl. 45, figs. 1-2. Early Triassic, Nevada.
H. tenuis Clarke, 1960, pp. 8-9, pl. 1, figs. 10-11. Late Mississippian, Scotland.
HINDEODELLINAE Hass, 1959, p. 378. A new subfamily which includes the following genera: *Hindeodella* Bassler, *Cervicornoides* Stauffer, *Kladognathus* Rexroad, *Tripodellus* Sannemann, and *Metaprioniodus* Huddle.
HINDEODELLOIDES Huddle em. Elias, 1959, pp. 156-157. Late Devonian and Lower Mississippian.
HINDEODINA Hass, 1959a, p. 382. *Hindeodina simplaria* Hass, 1959a. Early Mississippian.
H. simplaria Hass, 1959a, p. 382, pl. 48, fig. 17. Early Mississippian, Texas.
H. uncata Hass, 1959a, p. 383, pl. 47, fig. 6. Early Mississippian, Texas.
HISTIODELLA Harris, 1962, pp. 207-208. *Histiodella altifrans* Harris, 1962. Middle Ordovician.
H. altifrans Harris, 1962, pp. 208-209, pl. 1, figs. 4a-4c. Middle Ordovician, Oklahoma.
H. serrata Harris, 1962, p. 209, pl. 1, figs. 3a-3b. Middle Ordovician, Oklahoma.
Icriodus woschmidti Zeigler, 1960a, pp. 185-186, pl. 15, figs. 16-18, 20-22. Early Devonian, Germany.
Keislognathus simplex Ethington, 1959, pp. 280-281, pl. 40, figs. 9-10. Late Ordovician, Iowa.
Lambdagnatbus macrodentata Higgins, 1961, pp. 214-215, pl. 12, figs. 1-3, text-fig. 3. Late Mississippian, England.
LATERICRIODUS Müller, 1962a, pp. 114-116. *Icriodus latericrescens* Branson and Mehl, 1938. Lower ? Middle to Upper Devonian.
Ligonodina complectens Clarke, 1960, pp. 9-10, pl. 1, figs. 14-15. Late Mississippian, Scotland.
L. cragi Clarke, 1960, pp. 10-11, pl. 2, figs. 1-2. Late Mississippian, Scotland.
L. loisae Clarke, 1960, p. 11, pl. 2, fig. 3. Late Mississippian, Scotland.
L. singularis Hass, 1959a, pp. 384-385, pl. 46, figs. 14-17. Early Mississippian, Texas.
L. tortilis Sweet and Bergström, 1962, pp. 1230-1231, pl. 170, figs. 13, 14. Middle Ordovician, Alabama.
L. ultima Clarke, 1960, pp. 12-13, pl. 2, figs. 9, 11. Late Mississippian, Scotland.
LIGONODININAE Hass, 1959a, p. 378. A new subfamily which includes the following genera: *Ligonodina* Bassler, *Euprioniodina* Bassler, *Synprioniodina* Bassler, *Hindeodelloides* Huddle, and *Loxognathus* Graves and Ellison.
Lonchodina cristagalli Ziegler, 1960a, pp. 189-190, pl. 14, figs. 1, 3, 5. Early Devonian, Germany.
L. jovtschevi Budurov, 1959, pp. 114, 125, 128, pl. 1, figs. 15a, 15b; pl. 5, figs. 32a, 32b. Late Triassic, Bulgaria.
L. lungtanensis Ching, 1960, pp. 236, 245, pl. 1, figs. 5, 7; pl. 2, fig. 4. Early Permian China.
L. walliseri Ziegler, 1960a, pp. 188-189, pl. 14, figs. 2, 6, 7. Early Devonian, Germany.
LONCHODININAE Hass, 1959a, p. 378. A new subfamily which includes the following genera: *Lonchodina* Bassler, *Apatognathus* Branson and Mehl. *Curtognathus* Branson and Mehl. *Erismodus* Branson and Mehl, *Trichonodella* Branson and Mehl.
Loxognathus grandis Ethington, 1959, p. 281, pl. 40, fig. 6. Late Ordovician, Iowa.
Mestognathus bipluti Higgins, 1961, pp. 216-217, pl. 10, figs. 1, 2, text-fig. 4. Late Mississippian, England.
Metalonchodina conflecta Clarke, 1960, p. 17, pl. 2, fig. 14. Late Mississippian, Scotland.
Microcoelodus sweeti Stone and Furnish, 1959, p. 224, pl. 31, fig. 18. Late Ordovician, Wyoming.

NEOPRIONIODONTINAE Hass 1959a, p. 378. A new subfamily which includes the following genera: *Neoprioniodus* Rhodes and Müller, *Leptochirognathus* Branson and Mehl, *Loxodus* Furnish, *Pachysomia* Smith, and *Subprioniodus* Smith.

Neoprioniodus brevis Clarke, 1960, pp. 13-14, pl. 2, fig. 7. Late Mississippian, Scotland.

N. cassilaris (Branson and Mehl) em. Elias, 1959, pp. 153-154, pl. 2, figs. 17-21. Early Mississippian, Illinois.

N. cassilaris var. *keokukensis* Elias, 1959, p. 154, pl. 2, fig. 2. Early Mississippian, Illinois.

N. insolitus Hass, 1959a, pp. 383-384, pl. 48, figs. 19, 22. Early Mississippian, Texas.

N. lanceolatus Hass, 1959a, p. 384, pl. 46, figs. 1, 2, 8. Early Mississippian, Texas.

N. miseri Elias, 1959, p. 154, pl. 2, figs. 23, 24. Late Mississippian, Oklahoma.

N. nankingensis Ching, 1960, pp. 235, 244, pl. 1, fig. 2. Early Permian, China.

N. postinversus Helms, 1959, p. 644, pl. 2, fig. 6, text-fig. 1. Late Devonian, Germany.

N. rynikeri Elias, 1959, p. 152, pl. 2, fig. 15. Late Mississippian, Oklahoma.

N. spathatus Higgins, 1961, pp. 217-218, pl. 11, figs 2, 4, text-fig. 5. Late Mississippian, England.

Oistodus angulensis Harris, 1962, pp. 199-201, pl. 1, figs. 1a-1c. Middle Ordovician, Oklahoma.

O. basiovalis Sergeeva, 1963, pp. 96-98, pl. 7, figs. 6, 7, text-fig. 3. Early Ordovician, Russia.

O. bilongalus Harris, 1962, pp. 201-202, pl. 1, figs. 8, 9a, 9b, 10a-10c. Middle Ordovician, Oklahoma.

O. brevibasis Sergeeva, 1963, pp. 95-96, pl. 7, figs. 4-5, text-fig. 2. Early Ordovician, Russia.

O. multicorrugatus Harris, 1962, p. 204, pl. 1, figs. 2a-2c. Middle Ordovician, Oklahoma.

O. originalis Sergeeva, 1963, pp. 98-99, pl. 7, figs. 8-9, text-fig. 4. Early Ordovician, Russia.

O. robustus Bergström, 1961, p. 45, pl. 3, figs. 7-10, text-fig. 3F. Middle Ordovician, Sweden.

Oneotodus gallatini Müller, 1959c, p. 457, pl. 13, figs. 5-10, 12, 18. Late Cambrian, Wyoming.

O. tenuis Müller, 1959c, pp. 457-458, pl. 13, figs. 11, 13, 14, 20. Late Cambrian, South Dakota.

Oulodus casteri Pulse and Sweet, 1960, pp. 255-256, pl. 36, figs. 1, 8, 12. Late Ordovician, Ohio, Kentucky, and Indiana.

O. rohneri Ethington and Furnish, 1959, p. 544, pl. 73, figs 17-18. Late Ordovician, Manitoba.

Ozarkodina chengpanshanensis Ching, 1960, pp. 237-245, pl. 1, figs. 6, 8, 11. Early Permian, China.

O. hindei Clarke, 1960, p. 18, pl. 3, figs. 1, 6. Late Mississippian, Scotland.

O. lacera Helms, 1959b, p. 647, pl. 2, fig. 16; pl. 5, fig. 10. Late Devonian, Germany.

O. lungtanensis Ching 1960, pp. 236, 245, pl. 1, figs. 5, 7; pl. 2, fig. 4. Early Permian, China.

O. pseudotypica Lindström, 1959, pp. 441-442, pl. 4, figs. 17-18, text-fig. 3:4. Middle and Late Ordovician, England.

O. rhodesi Lindström, 1959, pl. 1, figs. 1-9, text-fig. 3:6. Middle and Late Ordovician, England.

O. spassovi Stefanov, 1962, pp. 83, 87-88, pl. 2, figs. 1-2. Middle Triassic, Bulgaria.

Palmatolepis deflectens sigmoidalis Ziegler, 1962b, pp. 56-57, pl. 3, figs, 24-28. Late Devonian, Germany.

P. glabra pectinata Ziegler, 1960a, pp. 8-9, pl. 2, figs. 3-5. Late Devonian, Germany.

P. helmsi Ziegler, 1962b, pp. 60-61, pl. 8, figs. 16, 17. Late Devonian, Germany

P. marginata clarki Ziegler, 1962b, pp. 62-65, pl. 2, figs 20-27, text-fig. 4. Late Devonian, Germany.

P. perlobata sigmoidea Ziegler, 1962b, pp. 71-72, pl. 8, figs. 7, 9-11. Late Devonian, Germany.

P. quadrautinodosa inflexoidea Ziegler, 1962b, pp. 74-75, pl. 5, figs. 14-18. Late Devonian, Germany.

P. q. marginifera Ziegler, 1960a, pp 11-12, pl. 1, fig. 6, pl. 2, figs. 6-8 Late Devonian, Germany.

P rugosa grossi Ziegler, 1960c, p 37, pl. 1, figs 1-2. Late Devonian, Germany.

P. r. postera Ziegler, 1960c, pp. 39-40, pl. 2, figs. 10-11. Late Devonian, Germany.

P. r. trachytera Ziegler, 1960c, pp. 38-39, pl. 1, fig. 6; pl. 2, figs. 1-9. Late Devonian, Germany.

Paltodus variabilis Sergeeva, 1963, pp. 99-100, pl. 7, figs. 10-12, text-fig. 5. Early Ordovician, Russia.
P. volchovensis Sergeeva, 1963, pp. 100-102, pl. 7, figs. 13-14, text-fig. 6. Early Ordovician, Russia.
PANDERODUS Ethington, 1959, p. 284. *Paltodus unicostatus* Branson and Mehl, 1933. Early Ordovician and Middle Silurian.
PARACHIROGNATHUS Clark, 1959, p. 311. *Parachirognathus ethingtoni* Clark, 1959. Early Triassic.
P. ethingtoni Clark, 1959, pp. 311-312, pl. 45, figs. 3, 5, 7. Early Triassic, Nevada.
P. geiseri Clark, 1959, p. 312, pl. 45, figs. 4, 8, 10, 11. Early Triassic. Nevada.
Paracordylodus lindstroemi Bergström, 1961, pp. 50-51, pl. 2, figs. 8-12, text-fig. 2c. Middle Ordovician, Sweden.
PLEGAGNATHUS Ethington and Furnish, 1959, p. 544. *Plegagnathus nelsoni* Ethington and Furnish, 1959. Late Ordovician.
P. nelsoni Ethington and Furnish, 1959, pp. 544-545, pl. 73, figs. 2-3. Late Ordovician, Manitoba.
Polygnathodella tenuis Clarke, 1960, p. 28, pl. 5, figs. 12, 13. Early Pennsylvanian, Scotland.
Polygnathus bicavata Ziegler, 1962b, pp. 86-87, pl. 10, figs. 1, 3, 6-8. Late Devonian Germany.
P. communis var. *bifurcata* Hass, 1959a, p. 390, pl. 48, figs. 11, 12. Early Mississippian, Texas.
P. c. var. *carina* Hass, 1959a, p. 391, pl. 47, figs 8, 9. Early Mississippian, Texas.
P. diversa Helms, 1959b pp. 650-651, pl. 5, figs. 5-8, text-fig. 2. Late Devonian, Germany.
Polyplacognathus rutriformis Sweet and Bergström, 1963, pp. 1237-1239, pl. 171, figs. 4, 5. Middle Ordovician, Alabama.
P. stelliformis Sweet and Bergström, 1963, pp. 1239-1240, pl. 171, figs. 1,2. Middle Ordovician, Alabama.
P. pura Voges, 1959b, p. 291, pl. 34, figs. 21-33. Early Mississippian, Germany.
P. p. pura Voges, 1959b. p. 291- 292, pl. 34, fig. 21-26. Early Mississippian, Germany.
P. p. subplana Voges, 1959b, pp. 292-293, pl. 34, figs. 27-33. Early Mississippian, Germany.
P. glabra bilobata Ziegler, 1962b, pp. 89-90, pl. 10, figs. 4, 5, 16, 17, 21. Late Devonian. Germany.
P. obliquicostata Ziegler, 1962b, pp. 92-93, pl. 11, figs. 8-12. Late Devonian, Germany.
Polylophodonta (?) *triphyllata* Ziegler, 1960a, pl. 1, fig. 5, pl. 2, figs. 1-2. Late Devonian, Germany.
P. vogesi Ziegler, 1962b, pp. 94-95, pl. 11, figs. 5-7. Late Devonian, Germany.
Prioniodella bončevi Spasov and Ganev, 1960, pp. 88, 93-94, pl. 2, figs. 4-6, 8. Late Triassic, Bulgaria.
P. delicatula Buhurov, 1959, pp. 120, 126-127, 129, pl. 1, figs. 17a, 17b; pl. 3, figs. 4, 5, 11a, 11b; pl. 5, fig. 33. Late Triassic, Bulgaria.
P. dropla Spasov and Ganev, 1960, pp. 87, 92-93, 94, pl. 2, figs. 7-10. Late Triassic, Bulgaria.
P. tzankovi Buhurov, 1959, pp. 120, 126, 129, pl. 1, figs. 18, 19a, 19b; pl. 3, figs. 12a, 12b, 14, 15. Late Triassic, Bulgaria.
Prioniodina bicurvata pronoides Walliser, 1960, p. 33, pl. 8, figs. 8-10. Late Silurian, Devon Island, Northwest Territories.
P. kotlensis Buhurov, 1959, pp. 122, 127, 129-130, pl. 5, figs. 10-11. Late Triassic, Bulgaria.
P. montellensis Clark, 1959, pp. 309-310, pl. 44, fig. 7. Early Triassic, Nevada.
P. pulcherrima Lindström, 1959, pp. 442-444, pl. 3, figs. 28-30. Middle and Late Ordovician, England.
P. rotunda Sweet, Turco, Warner and Wilkie, 1959, p. 1061, pl. 131, fig. 12; pl. 133, fig. 8. Late Ordovician, Ohio.
P. tzankovi Spasov and Ganev. 1960, pp. 89-90, 93-95, pl. 2, figs. 13, 14. Late Triassic, Bulgaria.
P. velicuspis Pulse and Sweet, 1960, pp. 259-260, pl. 36, figs. 5, 13. Late Ordovician, Ohio, Kentucky, and Indiana.
Prioniodus variabilis Bergström, 1961, pp. 51-53, pl. 2, figs. 1-7. Middle Ordovician, Sweden.
PRISTOGNATHUS Stone and Furnish, 1959, p. 226. *Pristognathus bighornensis* Stone and Furnish, 1959. Late Ordovician.

P. bighornensis Stone and Furnish, 1959, pp. 226-227, pl. 32, figs. 7, 8. Late Ordovician, Wyoming and Manitoba.

PROACODUS Müller, 1959c, p. 458. *Proacodus obliquus* Müller, 1959c. Late Cambrian.

P. obliquus Müller, 1959c, pp. 458-459, pl. 13, figs. 1, 2, 4. Late Cambrian, Germany.

PROBLEMATOCONITES Müller, 1959c. *Problematoconites perforata* Müller, 1959c. Late Cambrian.

P. perforata Müller 1959c, pp. 471-472, pl. 15, fig. 17. Late Cambrian, Germany.

Pseudopolygnathus brevipennata Ziegler, 1962b, pp. 98-99, pl. 12, figs. 1-7. Late Devonian, Germany.

P. granulosa Ziegler 1962b, pp. 99-100, pl. 11, figs. 25-30. Late Devonian, Germany.

P. lanceolata Hass, 1959a, pp. 391-392, pl. 47, figs. 19-26. Early Mississippian, Texas.

P. triangula Voges, 1959b, p. 301, pl. 34, figs. 51-66; pl. 35, figs. 1-13, text-fig. 5. Early Mississippian, Germany.

P. t. inaequalis Voges, 1959b, p. 302, pl. 34, figs. 51-58, text-fig. 5. Early Mississippian, Germany.

P. t. pinnata Voges, 1959b, pp. 302-304, pl. 34, figs. 59-66; pl. 35, figs. 1-6. Early Mississippian, Germany.

P. trigonica Ziegler, 1962b, pp. 101-102, pl. 12, figs. 8-13. Late Devonian, Germany.

PTILONCODUS Harris, 1962, pp. 206-207. *Ptiloncodus simplex* Harris, 1962. Middle Ordovician.

P. simplex Harris, 1962, p. 207, pl. 1, figs. 5a-5c, 6. Middle Ordovician, Oklahoma.

RHYNCHOGNATHODUS Ethington, 1959b, p. 1128. *Rhynchognathodus typica* (Ethington), 1959a. The name *Rhynchognathus* which was originally applied to this unit is prepoccupied as pointed out by Ethington in 1959b when he proposed this name. Late Ordovician.

R. aborodentata (Ethington), 1959a, pp. 286-287, pl. 41, figs. 1-2. Late Ordovician, Iowa.

R. typica (Ethington), 1959a, p. 286, pl. 41, figs. 3-4. Late Ordovician, Iowa.

Roundya bispicata Sweet and Bergström, 1963, p. 1243, pl. 171, fig. 6. Middle Ordovician, Alabama.

R. plana Helms, 1959b, pp. 654-655, pl. 6, fig. 26. Late Devonian, Germany.

R. prava Helms, 1959, p. 655, pl. 2, fig. 11. Late Devonian, Germany.

R. pyramidalis Sweet and Bergström, 1963, pp. 1243-1244, pl. 170, figs. 7-9. Middle Ordovician, Alabama.

Sagittodontus dahlmani Müller, 1959c, pp. 460-461, pl. 14, figs. 5, 7, 10. Late Cambrian, Germany.

S. dentatus Ethington, 1959, p. 287, pl. 39, fig. 13. Late Ordovician, Iowa.

S. dunderbergiae Müller, 1959c, p. 461, pl. 14, figs. 8, 9. Late Cambrian, Nevada.

S. eureka Müller, 1959c, pp. 461-462, pl. 14, fig. 6. Late Cambrian, Nevada.

Scandodus oelandicus Müller, 1959c, p. 463, pl. 12, figs. 14, 15, text-fig. 10. Late Cambrian, Germany.

S. rarus Müller, 1959c, pp. 463-464, pl. 12, fig. 12. Late Cambrian, Germany.

S. tortilis Müller, 1959c, p. 464, pl. 12, figs. 7, 8, 10. Late Cambrian, Germany.

S. unistriatus Sweet and Bergström, 1962, p. 1245, pl. 168, fig. 12, text-fig. 1E. Middle Ordovician, Alabama.

Scolopodus cornulformis Sergeeva, 1963, pp. 93-95, pl. 7, figs. 1-3, text-fig. 1. Early Ordovician, Russia.

S. giganteus Sweet and Bergström, 1962, p. 1247, pl. 169, fig. 14, text-fig 1j. Middle Ordovician, Alabama.

S. varicostatus Sweet and Bergström, 1962, pp. 1247-1248, pl. 168, figs. 4-9, text-fig. 1A, C, K. Middle Ordovician, Alabama.

Scutula (?) *tripodis* Helms, 1959b, p. 657, pl. 5, figs. 17a, 17b. Late Devonian, Germany.

Siphonodella cooperi Hass, 1959a, p. 392, pl. 48, figs. 35, 36. Early Mississippian, Texas.

S. obsoleta Hass, 1959a, pp. 392-393, pl. 47, figs. 1, 2. Early Mississippian, Texas.

SPATHOGNATHODONTINAE Hass, 1959a, p. 378. A new subfamily which includes the following genera: *Aphelognathus* Branson, Mehl, and Branson, *Bryantodina* Stauffer, *Centrognathodus* Branson and Mehl, *Dinodus* Cooper, *Elictognathus* Cooper, *Falcodus* Huddle, *Lambdagnathus* Rexroad, *Nodognathus* Cooper, *Oligodus* Cooper, *Pandorinellina* Hass, *Pinacognathus* Branson and Mehl, and *Spathognathus* Branson and Mehl.

Spathognathodus anteposicornis Scott, 1961, pp. 1224-1225, text-figs. 2H-2K. Late Devonian, Illinois.

S. bohlenanus Helms, 1959b, p. 658, pl. 6, figs. 5-8. Late Devonian, Germany.

S. canadensis Walliser, 1960, p. 34, pl. 8, figs. 1-3. Late Silurian, Devon Island, Northwest Territories.
S. collinsoni Scott, 1961, pp. 1225-1226, text-figs. 2A-2D. Late Devonian, Illinois.
S. cooperi Hass, 1959a, pp. 387-388, pl. 48, figs. 16, 20. Early Mississippian, Texas.
S. culminidirectus Scott, 1961, pp. 1226-1227, text-figs. 2E-2G. Late Devonian, Illinois.
S. exodentatus Clarke, 1960, pp. 19-20, pl. 3, figs. 7, 8. Late Mississippian, Scotland.
S. longus Hass, 1959a, p. 388, pl. 48, figs. 9, 13, 14. Early Mississippian, Texas.
S. pusillus Clarke, 1960, pp. 20-21, pl. 3, figs. 10, 11. Late Mississippian, Scotland.
S. remscheidensis Ziegler, 1960a, pp. 194-195, pl. 13, figs. 1, 2, 4, 5, 7, 8, 10, 14. Early Devonian, Germany.
S. supremus Ziegler 1962b, pp. 114-115, pl. 13, figs. 20-26. Late Devonian, Germany.
S. werneri Ziegler, 1962b, pp. 115-116, pl. 13, figs. 11-16. Late Devonian, Germany.
S. whitei Rhodes, 1963, pp. 404-405, pl. 47, figs. 4, 9, 10, 25, 26. Early Permian, Wyoming.
Staurognathus anchoraria Hass, 1959a, p. 393, pl. 46, figs. 12, 13, 21. Early Mississippian, Texas.
Streptognathodus parallelus Clarke, 1960, p. 29, pl. 5, figs. 6, 8, 14, 15. Late Mississippian, Scotland.
S. unicornis Rexroad and Burton, 1961, p. 1157, pl. 138, figs. 1-9. Late Mississippian, Illinois.
Subbryanthodus abstractus Clark and Ethington, 1962, pp. 112-113, pl. 1, figs. 16, 20-21; pl. 2, fig. 2. Early Permian, Texas, Wyoming, Idaho, Arizona.
S. subaequalis Higgins, 1961, pp. 218-219, pl. 12, fig. 15, text-fig. 6. Late Mississippian, England.
Synprioniodina denticamura Rexroad and Liebe, 1962, p. 513, text-fig. 2. Late Mississippian, Illinois.
S. kufengensis Ching, 1960, pp. 237-245, pl. 1, figs. 9, 10. Early Permian, China.
Tetraprioniodus asymmetricus Bergström, 1961, pp. 55-56, pl. 2, figs. 15-17. Middle Ordovician, Sweden.
T. lindstroemi Sweet and Bergström, 1962, pp. 1248-1249, pl. 170, figs. 5-6. Middle Ordovician, Alabama.
T. minax Sergeeva, 1963, pp. 102-103, pl. 8, figs. 1-3, text-fig. 7. Early and Middle Ordovician, Russia.
T. parvus Ethington, 1959, pp. 288-289, pl. 40, fig. 8. Late Ordovician, Iowa.
Trichonodella angulata Sweet, Turco, Warner, and Wilkie, 1959, p. 1064, pl. 131, figs. 9, 13. Late Ordovician, Ohio and Kentucky.
T. insolita Ethington, 1959, p. 290, pl. 41, figs. 10-11. Late Ordovician, Iowa.
T. parabolica Lindström, 1959, p. 450, pl. 1, figs. 18-22. Middle and Late Ordovician, England.
T. subundulata Sweet, Turco, Warner, and Wilkie, 1959, p. 1065, pl. 131, figs 2, 5, 10. Late Ordovician, Ohio.
Tripodellus tenuis Helms, 1959b, p. 659, pl. 2, fig. 14; pl. 5, fig. 19; pl. 6, fig. 22. Late Devonian.
TVAERENOGNATHUS Bergström, 1961, pp. 56-57. *Tvaerenognathus ordovicia* Bergström, 1961. Middle Ordovician.
T. ordovicica Bergström, 1961, pp. 57-58, pl. 1, figs. 1-5. text-fig. 2F. Middle Ordovician, Sweden.
WESTERGAARDODINA Müller, 1959c, pp. 465-467, *Westergaardodina biscuspidata* Müller, 1959c. Middle Cambrian and Early Ordovician.
W. amplicava Müller, 1959c, pp. 467-468, pl. 14, figs. 13, 14. Late Cambrian, Germany.
W. biscuspidata Müller, 1959c, p. 468, pl. 15, figs. 1, 4, 7, 9, 10, 14. Late Cambrian, Germany.
W. bohlini Müller, 1959c, p. 469, pl. 15, fig. 6. Late Cambrian, Germany.
W. kleva Müller, 1959c, p. 469, pl. 15, fig. 2. Late Cambrian, Germany.
W. mössebergensis Müller, 1959c, p. 470, pl. 14, figs. 11, 12, 15. Late Cambrian, Germany.
W. tricuspidata Müller, 1959c, p. 470, pl. 15, figs. 3, 5, 6. Late Cambrian, Germany.
Zygognathus crugensis Lindström, 1959, p. 451, pl. 1, figs. 11-15, text-fig. 3:5. Middle and Late Ordovician, England.
Z. maysvillensis Pulse and Sweet, 1960, p. 262, pl. 37, figs. 9, 12. Late Ordovician, Ohio, Indiana, and Kentucky.

HOMONYMS AND SYNONYMS

Ancyroides Miller and Youngquist, 1947, pp. 502, 504, is a junior subjective synonym of *Ancyrognathus* Branson and Mehl, 1934, pp. 181, 184, 240, according to Hass, 1959a, p. 379.

Ancyropenta Müller and Müller, 1957, pp. 1092-1093, is a junior subjective synonym of *Ancyrodella* Ulrich and Bassler, 1926, pp. 6, 43-44, 48, according to Hass, 1959a, p. 379.

Ctenognathodus Fay, 1959, p. 195, is a junior subjective synonym of *Spathognathodus* Branson and Mehl, 1941. See Ziegler, 1961.

Ctenognathus Pander, 1856, p. 32, is preoccupied by *Ctenognathus* Fairmaire, 1843. Renamed *Ctenognathodus* Fay, 1959, p. 195, which is a junior subjective synonym of *Spathognathodus* Branson and Mehl, 1941, p. 98. See Ziegler, 1961; Hass, 1959a, p. 379; Lindström, 1960b.

Deflectolepis Müller, 1956, pp. 16-17, is a junior subjective synonym of *Panderodella* Bassler, 1925, p. 220, according to Hass, 1959a, pp. 369, footnote 1, 379.

Ellisonia Müller, 1956, p. 822, is a junior subjective synonym of *Hibbardella* Bassler, 1925, p. 219, according to Hass, 1959a, p. 379.

Eoligonodina Branson, Mehl, and Branson, 1951, pp. 14-15, is a junior subjective synonym of *Zygognathus* Branson, Mehl, and Branson, 1951, pp. 11-12, according to Hass, 1959a, p. 379.

Idiognathodus Harris and Hollingsworth, 1933, p. 201, is a junior synonym of *Cavusgnathus* Harris and Hollingsworth, 1933, p. 200 as pointed out by Merrill, 1963.

Kladognathus Rexroad, 1958, p. 19, is preoccupied by *Cladognathus* Burmeister, 1847, p. 364. Renamed *Cladognathodus* by Rexroad, 1961, p. 6.

Lepodus Branson and Mehl, 1933, p. 37, is preoccupied by *Lepodus* Rafinesque, 1810. Renamed *Lepognathodus* Mehl, 1959. See Fay, 1959, p. 195.

Manticolepis Müller, 1956, p. 16, is a junior subjective synonym of *Palmatolepis* Ulrich and Bassler, 1926, pp. 6, 43-44, 49, according to Hass, 1959a, p. 380.

Multioistodus Cullison, 1938, pp. 219, 226, is a junior subjective synonym of *Belodus* Pander, 1856, pp. 30, 33, 90, according to Hass, 1959a, p. 380.

Neoprioniodus lanceolatus Ching, 1960, pp. 235, 244, is preoccupied by *Neoprioniodus lanceolatus* Hass, 1959a, p. 384.

Paltodus variabilis Sergeeva, 1963, pp. 99-100, pl. 7, figs. 10-12, text-fig. 5. is a junior homonym of *P. variabilis* Furnish, 1938, as pointed out by Branson, 1963, p. 224.

Pandorina Stauffer, 1940, p. 428, is preoccupied by *Pandorina* Bory de St. Vincent, 1827, and *Pandorina* Scacchi, 1833. Renamed *Pandorinellina* Hass, 1959a, pp. 378-379.

Polygnathodella Harlton, 1933, pp. 4-5, 15, is a junior synonym of *Idiognathoides* Harris and Hollingsworth, 1933, pp. 193-194, according to Hass, 1959a, p. 380.

Prioniodella Bassler, 1925, p. 219 is a junior synonym of *Prioniodina* Bassler, 1925, p. 219, according to Hass, 1959a, p. 380.

Prionognathus Pander, 1856, p. 34, is preoccupied by *Prionognathus* Ferté-Sénèctere, 1851. Renamed *Prionognathodus* Fay, 1959, p. 195.

Rhynchognathus Ethington, 1959a, p. 286, is preoccupied by *Rhynchognathus* Jaekel, 1929, p. 60. Renamed *Rhynchognathodus* Ethington, 1959b, p. 1128.

Valentia Smith, 1907, p. 251, is preoccupied by *Valentia* Stål, 1865. Renamed *Scotlandia* Cossmann, 1909, p. 68. See Fay, 1959, p. 195.

NEW NAMES

Cladognathodus Rexroad and Collinson, 1961, p. 6. New name for *Cladognathus* Rexroad, 1957, p. 28, and *Kladognathus* Rexroad, 1958, p. 19, which are preoccupied by *Cladognathus* Burmeister, 1847.

Gnathodus commutatus homopunctatus Ziegler, 1960b, p. 5. New name for *Gnathodus commutatus punctatus* Bischoff, 1957, p. 24, which is preoccupied by *Dryphenitus punctatus* Cooper, 1939.

Lepognathodus Mehl, 1959. New name for *Lepodus* Branson and Mehl, 1933, p. 37, which is preoccupied by *Lepodus* Rafinesque, 1810, as pointed out by Fay, 1959, p. 195.

Pandorinellina Hass, 1959a, pp. 378-380. New name for *Pandorina* Stauffer, 1940, p. 428, which is preoccupied by *Pandorina* Bory de St. Vincent, 1827; Scacchi, 1833.

Prionognathodus Fay, 1959, p. 195. New name for *Prionognathus* Pander, 1856, p. 34, which is preoccupied by *Prionognathus* Ferté-Sénèctere, 1851.

Scotlandia Cossmann, 1909, p. 68. New name for *Valentia* Smith, 1907, p. 251, which is preoccupied by *Valentia* Stål, 1865, as pointed out by Fay, 1959, p. 195, and Hass, 1959a, p. 380.

ERRATA AND CORRECTIONS TO INDEX OF CONODONTS, 1949-1958.

Five errors have been noted in the previous index of conodonts (Ash, 1961, pp. 229-237) as shown below: On page 230 authorship of *Avignathus* and *Avignathus beckmanni* was incorrectly assigned to Lys, Serre, and Deroo whereas the authors are Lys and Serre.
On page 235 *Polygnathus styriaca* was incorrectly spelled *Polygnathus styriaea.*
On page 235 authorship of *Polygnathus styriaca* and *Prioniodina bischoffi* was incorrectly assigned to Flugel and Ziegler whereas the author is Ziegler.
The corrected entires should read as follows:
Page 230.
Avignathus Lys and Serre, 1957, pp. 797-798. *Avignathus beckmanni* Lys and Serre, 1957. Late Devonian.
A. beckmanni Lys and Serre, 1957, p. 798, text-figs. 2a-2b. Late Devonian, Germany.
Page 235.
Polygnathus styriaca Ziegler, 1957, p. 47, pl. 1, figs. 11-13. Late Devonian, Germany.
Prioniodina bischoffi Ziegler, 1957, p. 48, pl. 4, fig. 5. Late Mississippian, Germany.

INDEX OF CONODONT-BEARING FORMATIONS

Names of conodont-bearing formations and faunal zones mentioned in the articles listed in the bibliographic section of this paper are indexed here. Formations and faunal zone are listed alphabetically under the appropriate geologic series as used by the U. S. Geological Survey together with the name of the author and the publication date of the articles which indicate that the unit contains conodonts. Nomenclature used in this report is adapted from the published sources. An asterisk (*) precedes the publication date of articles in which faunal lists are included for the indicated formation or zone.

CAMBRIAN (UNDIVIDED)
Unnamed formation:
Australia - Ludbrook, 1963.
Germany - Müller, 1960a.
Nevada - Müller, 1960a.
Oklahoma - Müller, 1960a.
South Dakota - Müller, 1960a.
Sweden - Müller, 1960a.
Utah - Müller, 1960a.
Wyoming - Müller, 1960a.

MIDDLE CAMBRIAN
Gros Ventre Formation:
Wyoming - Koucky, Cygan, and Rhodes, *1961; Müller, *1959c.
Lejopyge laevigata Zone:
Sweden - Westergård, 1940, 1953.
Olygomys exporrecta conglomerate:
Sweden - Westergård, 1953.
Orusia lenticularis conglomerate:
Sweden - Westergård, 1922.
Solenopleura brachymetopa Zone:
Sweden - Westergård, 1953.
Zone of *Ptychagnostus* (*Triplagnostus*) *gibbus* (B_1):
Sweden - Müller, *1959.

UPPER CAMBRIAN
Acerocare - Parabolina heres Zone:
Sweden - Westergård, 1953.
Arbuckle Limestone:
Texas - Barnes, Cloud and others, *1959.

Chatsworth Limestone:
Queensland, Australia - Jones, P. J., 1961.
Conaspis - Zone:
Wyoming - Müller, *1959c.
Deadwood Formation:
South Dakota - Müller, *1959c.
Williston Basin - Echols, 1961.
Also see Little Elk Member.
Dunderberg Shale:
Nevada - Müller, *1959c.
Eoorthis subzone of the *Conaspis* Zone:
Utah - Müller, *1959c.
Gallatin Limestone:
Wyoming - Koucky, Cygan and Rhodes, *1961; Müller, *1959c.
Gros Ventre Formation:
Wyoming - Goodwin, 1962.
Little Elk Member of the Deadwood Formation:
South Dakota - Müller, *1959c.
Mungerebar Limestone:
Queensland, Australia - Jones, P. J., *1961.
Olenus Zone:
Sweden - Westergård, 1953.
Orusia lenticularis conglomerate - listed under Middle Cambrian.
Orusia-Peltur-Ctenopyge Zone:
Sweden - Westergård, 1953.
Peltura-Ctenopyge Zone:
Sweden - Westergård, 1953.
Signal Mountain Formation:
Oklahoma - Müller. *1959c.
Windfall Formation:
Nevada - Müller, *1959c.
Zones 1, 2, 3, 4, 5, 5c, 5d, 5e, and 5f:
Sweden - Müller, *1959c.
Zones 1, 2, 3, 5b, and 5d:
Germany - Müller, *1959c.

ORDOVICIAN (UNDIVIDED)
Unnamed formation:
Australia - Ludbrook, 1963.

LOWER ORDOVICIAN
Ceratopyge Shale:
Sweden - Westergård, 1953; Wiman, 1893.
Deadwood Formation (upper part):
North Dakota - Carlson, *1960.
El Paso Limestone:
Texas - Ash, 1962; Ellison, 1962a.
Erratic boulders:
Poland - Wolska, *1961.
Expansus Limestone:
Sweden - Lindström, *1960a.
Gigas Limestone:
Sweden - Lindström, *1960a.
Grove Creek Formation:
Wyoming - Goodwin, 1962.
Honeycut (?) Formation:
Texas - Barnes, Cloud, and others, 1959.
Jefferson City Dolomite:
Missouri - Unklesbay, *1952.
Kunda horizon:
Russia - Sergeeva, *1963.
Leetse Stage (B_1) of the Ontiken Subseries of the Oelandiar Series:
Estonia - Rõõmusoks, 1960.

Lepidurus Limestone:
Sweden - Lindström, *1960a.
Limbata Limestone:
Sweden - Lindström, *1960a.
Lower *Dicellograptus* Shales:
Sweden - Nilsson, *1960.
Lower *Didymograptus* Shales:
Sweden - Tjernvik, *1960.
Middle *Dicellograptus* Shales:
Sweden, Nilsson, *1960.
Oelandiar Series - see Leetse Stage (B_2) of the Ontiken Subseries
Ontiken Subseries - see Leetse Stage (B_1).
Pander Greensand:
Western Australia - Teichert, 1958.
Prairie du Chien Group:
Minnesota - Echols, 1959.
Upper Mississippi and Minnesota River Valleys - Echols, 1959.
Raniceps Limestone:
Sweden - Lindström, *1960a.
Unnamed formation:
Mexico - Bridges and DeFord, 1960.
Volkhov horizon:
Russia - Sergeeva, *1963.

MIDDLE ORDOVICIAN
Crassicauda Limestone:
Sweden - Lindström, *1960a.
Crug Limestone:
England - Lindström, *1959, *1960b.
Cynthiana Formation:
Kentucky - Kesling, 1961; 1963.
Ohio - Kesling, 1961; 1963.
Erratic boulders:
Poland - Wolska, *1961.
Galena Formation - see Prosser Member. Also listed under Upper Ordovician.
Harding Formation:
Colorado - Chronic, 1961; Sweet, 1961.
Harding Formation equivalent:
Wyoming - Koucky, Cygan, and Rhodes, *1961.
Ice Box Member of the Winnipeg Sandstone:
North Dakota - Carlson, *1960.
South Dakota - Carlson, *1960.
Joins Creek Formation:
Oklahoma - Harris, *1962; Sweet, 1963.
Ludibundus Limestone:
Sweden - Hessland, 1960; Strachan, 1960.
Normanskill Shale:
Maine - Hessland, 1962; Sweet and Bergström, *1962.
Oil Creek Formation of the Simpson Group:
Oklahoma - Echols, 1961.
Platteville Formation:
Minnesota - Echols, 1959.
Platyurus Limestone:
Sweden - Lindström, *1960a.
Pratt Ferry Formation:
Alabama - Kesling, 1959, 1960, 1961; Sweet and Bergström, *1962.
Prosser Member of the Galena Formation:
Iowa - Ethington, *1959.
Roughlock Member of the Winnipeg Sandstone:
North Dakota - Carlson, *1960.
South Dakota - Carlson, *1960.
Schroeteri Limestone:
Sweden - Lindström, *1960a.
Simpson Group - see Oil Creek Formation.

Tallinn horizon:
Russia - Sergeeva, *1963.
Trenton Limestone:
New York - Kesling, 1960.
Ontario - Kesling, 1960.
Unnamed formation:
Kentucky - Kesling, 1960.
Upper unit of the Winnipeg Sandstone:
Manitoba - Carlson, *1960.
Also see Ice Box and Roughlock Members of the Winnipeg Sandstone.

UPPER ORDOVICIAN
Beaverfoot Limestone:
British Columbia - Echols, 1963.
Bighorn Dolomite:
Wyoming - Jones, *1960.
See also Lander Sandstone and Leigh Dolomite Members of the Bighorn Dolomite.
Brisco Formation:
British Columbia - Echols, 1963.
Cape Phillips Formation:
Northwest Territories, Canada - Ethington, 1959.
Crug Limestone:
England - Hessland, 1960; Lindström, *1959, *1960b.
Dubuque Member of the Galena Formation:
Iowa - Ethington, *1959.
Eden Group:
Indiana - Sweet, 1959.
Kentucky - Douglass, 1960; Kesling, 1959; Sweet, 1959.
Ohio - Douglass, 1960; Kesling, 1959; Pulse and Sweet, *1960; Sweet, 1959.
Also see Fulton Shale, Economy, McMicken, and Southgate Shale Members.
Ely Springs Dolomite:
Nevada - Carss and Langenheim, *1963; Langenheim and others, 1962.
Erratic boulders:
Poland - Wolska, *1960.
Fairview Formation:
Indiana - Kesling, 1960; Pulse and Sweet, *1960; Sweet, *1959.
Kentucky - Kesling, 1960; Pulse and Sweet, *1960; Sweet, *1959.
Ohio - Kesling, 1960; Pulse and Sweet, *1960; Sweet, *1959.
Fulton Shale and Economy Member of the Latonia Shale of the Eden Group:
Kentucky - Sweet, Turco, Warner, and Wilkie, *1959.
Ohio - Sweet, Turco, Warner, and Wilkie, *1959.
Galena Formation - See Stewartville and Dubuque Members.
Also listed under Middle Ordovician.
Gelli-grin Limestone:
England - Lindström, *1959.
Gunn Member of the Stony Mountain Formation:
Manitoba, Canada - Ethington and Furnish, 1959, *1960.
Keisley Limestone:.
England - Lindström, *1959.
Lander Sandstone Member of the Bighorn Dolomite:
Wyoming - Koucky, Cygan, and Rhodes, *1961.
Leigh Dolomite Member of the Bighorn Dolomite:
Wyoming - Koucky, Cygan, and Rhodes, *1961; Stone and Furnish, *1959.
McMicken Member of the Eden Formation:
Ohio - Sweet, Turco, Warner, and Wilkie, *1959.
McMillan Formation of the Maysville Group:
Indiana - Sweet, 1959; Kesling, 1960; Pulse and Sweet, *1960.
Kentucky - Sweet, 1959; Kesling, 1960.
Ohio - Sweet, 1959; Kesling, 1960; Pulse and Sweet, *1960.
Maysville Group:
Ohio - Kesling, 1959, 1960.
Also see McMillan Formation.
Montoya Limestone:
Texas: Ash, 1962; Ellison, 1962a.

Ottawa Fomation:
Ontario - Echols, 1963.
Pen-y-garnedd Limestone:
England - Lindström, *1959.
Richmond Group:
Indiana - Sweet, *1959.
Kentucky - Sweet, *1959.
Ohio - Sweet, *1959.
Shamattawa Limestone:
Manitoba, Canada - Ethington, 1959; Ethington and Furnish, *1959; Stone and Furnish, *1959.
Southgate Shale Member of the Latonia Shale of the Eden Group:
Ohio - Sweet, Turco, Warner, and Wilkie, *1959.
Stewartville Member of the Galena Formation:
Iowa - Ethington, *1959.
Stony Mountain Shale - see Gunn Member.
Unnamed formation:
France - Remack-Petitot, *1960.
Mexico - Bridges and DeFord, 1961.
Winnipeg Formation:
North Dakota - Echols, 1959, 1961.
Also listed under Middle Ordovician.

SILURIAN (UNDIVIDED)
Unnamed formation:
Illinois - Echols, 1961.
Indiana - Kesling, 1962.
Western Australia - Teichert, 1958.

LOWER SILURIAN
Chimneyhill Formation:
Oklahoma - Echols, 1961; Ireland, 1961.
Also see Clarita and Cochrane Members.
Clarita Member of the Chimneyhill Formation:
Oklahoma - Amsden, 1960.
Cochrane Limestone Member of the Chimneyhill Formation:
Oklahoma - Amsden, 1960.
Unnamed formation:
Algeria - Remack-Petitot, *1960.

MIDDLE SILURIAN
"Calizas alabeadus" (Santi Petri-Kalk):
Spain - Colom, 1959.
Chimneyhill Formation - listed under Lower Silurian.
St. Clair Limestone:
Arkansas - Amsden, 1960.
Unnamed formation:
England - Echols, 1959.
Upper Haugh Wood Bed:
England - Squirrell and Tucker, 1960.

UPPER SILURIAN
Beyrichia Limestone:
Germany - Walliser, *1960a.
Bodenham Beds - see Lower and Upper Bodenham Beds.
"Calizas alabeadas" (Santi Petri-Kalk):
Spain - Colom, 1959.
Henryhouse Formation:
Oklahoma - Amsden, 1960.
Lower Bodenham Beds:
England - Squirrell and Tucker, *1960.
Lower Perton Beds:
England - Squirrell and Tucker, *1960.
Perton Beds - see Lower and Upper Perton Beds.

Rushall Beds:
England - Squirrell and Tucker, 1960.
Sutherland River Formation:
Northwest Territories, Canada - Walliser, *1960a.
Unnamed formations:
Algeria - Cuvillier, 1962a; Remack-Petitot, *1960.
Bulgaria - Spasov, *1960.
England - Echols, *1959.
Germany - Pietzsch, 1960.
Rio De Oro (Spanish Sahara) - Echols, 1963; Ethington and Furnish, *1962.
Yugoslavia - Spasov, *1960.
Upper Bodenham Beds:
England - Squirrell and Tucker, *1960.
Upper Perton Beds:
England - Squirrell and Tucker, *1960.

DEVONIAN (UNDIVIDED)
Calcaire de Chalonnes:
France - Serre and Lys, 1959.
Unnamed formations:
Arizona - Anderson, 1962; Ethington, *1962.
Spain - Drooger, 1962.
Texas - Graves, *1954.
Utah - Jones, 1960.
Western Australia - Crespin, 1959.

LOWER DEVONIAN
Bois D'Arc Formation - see Cravatt Member.
Calcaire de Le Meignanne:
France - Serre and Lys, *1959.
Calcaire de Vern:
France - Serre and Lys, *1959.
"Calizas alabeadas" (Santi Petri-Kalk):
Spain - Colom, 1959.
Cravatt Member of the Bois D'Arc Formation:
Oklahoma - Amsden, 1960.
Frisco Formation:
Oklahoma - Amsden, 1960.
Ockrigen Kalke:
Germany - Ziegler, *1960a.
Princeps-Kalk:
Germany - Schriel, *1960a.
Unnamed formation:
France - Remack-Petitot, *1960; Serre and Lys, *1960.
Germany - Reichstein, *1959.
Algeria - Cuvillier, 1962a; Remack-Petitot, *1960.

MIDDLE DEVONIAN
Bandsschiefer:
Germany - Schriel, *1960b.
Buntschiefer:
Germany - Schriel, *1960b.
Calcaire d'Angers:
France - Erben, *1960.
Calcaire de Chaudefonds:
France - Serre and Lys, *1959.
"Calizas alabeadas" (Santi Petri-Kalk):
Spain - Colom, 1959.
Canutill Formation:
Texas - Ellison, 1962a.
Carrière de Blacourt:
France - Serre and Lys, *1960.
Couvinien inférieur:
Belgium - Serre and Lys, *1960.

dubia - rotundiloba Subzone:
Germany - Reichstein, 1960a.
Eifelquarzit:
Germany - Klitzsch, *1959; Erben, *1960.
Flinz:
Germany - Schriel and Stoppel, *1958a.
Fortune Formation:
Missouri - Echols, 1959.
Greifensteinerkalk:
Germany - Erben, *1960.
Kalkiger Lagerhorizont:
Germany - Reichstein, *1960a.
La Grange:
France - Serre and Lys, *1959.
Lower Banderschiefer:
Germany - Klitzsch, *1959.
Mangshan Sandstone:
China - Ching, 1960.
Mittel-devonischer Flinz:
Germany - Lutzens, *1959.
Odershäuser Kalk:
Germany - Schriel and Stoppel, *1958.
Plattenschieferübergangszone:
Germany - Lutzens, *1959.
Styliolinenkalkes:
Germany - Reichstein, *1959.
Unnamed formation:
Algeria - Remack-Petitot, *1960.
France - Remack-Petitot, *1960.
England - House, 1963.
Germany - Reuter, 1959; Schriel and Stoppel, *1958a, 1958b; Trautwein and Wittekindt, *1960; Ziegler, *1960b.
Mexico - Bridges and DeFord, 1961.
Rio de Oro (Spanish Sahara) - Panseri, *1959.
Texas - Peirce, 1962.
Usingerkalk:
Germany - Rietschel, 1961.
Varca - Zeit:
Germany - Kutscher, 1960.

UPPER DEVONIAN
Adorf - Stufe:
Germany - Krebs, *1960a; Rietschel, *1961; Schriel and Stoppel, *1958, *1960.
Arkansas group:
Arkansas - Branson, 1959.
Oklahoma - Branson, 1959.
Arkansas Novaculite:
Arkansas - Elias, 1959.
Bandkalk:
Germany - Lutzens, *1959.
Bohlen profils:
Germany - Helms, 1959a.
Büdesheimer Schiefer mit Kellwasserkalk:
Germany - Schriel and Stoppel, 1958a.
Bugle Gap Formation:
Western Australia-Glenister and Crespin, *1959.
Burt Range Limestone:
Northern Territory, Australia - Glenister, *1960.
Carrière de Diou:
France - Guffroy, *1959; Lys, Serre, Mauvier, and Grekoff, *1961.
Carrière de Fontête:
France - Guffroy, *1959; Lys, Serre, Mauvier, and Grekoff, *1961.
Carrière de Gilly:
France - Guffroy, *1959; Lys, Serre, Mauvier, and Grekoff, *1961.

Cassadaga Stage:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Cashaqua Shale Member of the Sonyea Formation - see Parrish Limestone Bed.
Chattanooga Shale:
Mississippi River Valley - Weller, 1960.
Tennessee - Conant and Swanson, 1961.
Cheiloceras Stufe:
France - Ziegler, *1959b.
Germany - Ziegler, *1960b.
Spain - Ziegler, *1959b.
Chemung:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Crosby Sandstone:
New York - Hass, *1959b.
Crystal Pass Limestone:
Nevada- Langenheim and Collinson, *1963.
"Cypridinenschiefers":
Germany - Helms, 1960b.
Darby Formation:
Montana - Echols, 1961.
Wyoming - Echols, 1959, 1961.
Dasberg-Stufe:
Germany - Schriel and Stoppel, *1960.
Devils Gate Limestone:
Nevada - Clark and Becker, *1960.
Dillenburger Tuffe:
Germany - Krebs, 1960b.
Dunkirk Shale Member of the Perrysburg Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
dubia-rhenana-Interregnum:
Germany - Krebs, *1959.
Englewood Formation:
South Dakota - Klapper and Furnish, *1962.
F_2g:
Belgium - Serre and Lys, *1960.
F_2i:
Belgium - Serre and Lys, *1960.
Fairfield Beds:
Western Australia - Glenister and Crespin, *1959.
Flaserkalk:
Germany - Rietschel, *1961.
Flasrige Kalkbänderschiefer:
Germany - Lutzens, *1959.
Gardner Formation:
Utah - Beach, *1961; Clark and Beach, 1962.
Genundewa Limestone Member of the Genesee Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Genesee Formation - See Geneseo Shale Member, Genundewa Limestone Member, Ithaca Member, Renwick Shale Member, Sherburne Flagstone Member, and West River Shale Member.
Geneseo Shale Member of the Genesee Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Givet-Stufe:
Germany - Krebs, *1960a.
Glen Park Formation:
Missouri - Mehl, 1960.
Gogo Formation:
Western Australia - Glenister, *1960; Glenister and Crespin, *1959.

Gonioclymenia-Stufe:
Germany - Ziegler, *1960b.
Grassy Creek Shale:
Missouri - Howe and Koenig, 1961; Mehl, 1960; Unklesbay, *1952.
Upper Mississippi Valley - Collinson, Scott and Rexroad, 1962a; 1962b.
Hauptquartzit:
Germany - Reichstein, *1961.
Hemberg-Stufe:
Germany - Krebs, *1960a; Rietschel, *1961; Schriel and Stoppel, *1960.
Hercynkalkes:
Germany - Jordan, *1960.
Holt's Summit Formation:
Missouri - Echols, 1959; Mehl, 1960.
Huron Shale:
Ohio - Hoover, 1960.
Ithaca Member of the Genesee Formation:
New York - Hass, *1959b.
Kalkknotenschiefer:
Germany - Helms, *1959b.
Kieselkalk:
Germany - Lutzens, *1959.
Kieselschiefer:
Germany - Schriel and Stoppel, *1958a.
Kiesel-und Wetzschieferzone:
Germany - Lutzens, *1959.
Kleinknotiger Kalk:
Germany - Helms, *1959b.
Lime Creek Shale:
Iowa - Dow, 1960.
Liegende Alaunschiefer:
Germany - Patteisky and Schönwälder, *1960.
Louisiana Limestone:
Illinois - Collinson and Swann, 1958; Scott, *1961.
Missouri - Mehl, 1960.
Upper Mississippi Valley - Collinson, Scott and Rexroad, 1962.
Manticoceras-Stufe:
Germany - Hosel, *1960; Ziegler, *1959a, *1960b.
Maple Mill Shale:
Upper Mississippi Valley - Collinson, Scott and Rexroad, 1962.
Martin Limestone:
Arizona - Ash, 1962; Ethington, *1962.
Massie Creek Sandstone:
Missouri - Mehl, 1960.
Middlesex Shale Member of the Sonyea Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Mittlerer Kalkknollenschiefer:
Germany - Helms, *1959b.
Nehden-Stufe:
Germany - Krebs, *1960a; Rietschel, *1961; Schriel and Stoppel, *1960.
New Albany Shale:
Indiana - Gutschick and Treckman, 1957; Mehl, 1960.
Noel Shale:
Missouri - Echols, 1959, 1961; Huffman and Stark, 1960; Mehl, 1960.
Ober-devonischer Flinz:
Germany - Lutzens, *1959.
Ober *Platyclymenien*-Stufe:
Germany - Hosel, 1960.
Ortberggrauwacke:
Germany - Schriel and Stoppel, *1958a.
Oxyclymenien-Stufe:
Germany - Hosel, 1960.
Spain - Ziegler, *1959b.

Parrish Limestone Bed of Cashaqua Shale Member of the Sonyea Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Perrysburg Formation - see Dunkirk Shale Member.
Pilot Shale:
Nevada - Clark and Becker, *1960.
Utah - Baer, *1962, Clark and Becker, *1960.
Pinyon Peak Limestone:
Utah - Beach, *1961; Clark and Beach, 1962; Clark and Becker, *1960.
Plattenkalsteinserie:
Germany - Rabien and Krebs, 1959.
Plattenkalk:
Germany - Rietschel, *1961.
Plattenschiefer:
Germany - Schriel and Stoppel, *1958a.
Plattige Kalkbänderschiefer:
Germany - Lutzens, *1959.
Platyclymenia-Stufe:
France - Ziegler, *1959b.
Portal Formation:
Arizona - Ash, 1962; Ethington, 1962.
Renwick Shale Member of the Genesee Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Rhinestreet Shale Member of the West Falls Formation:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Roaring River Sandstone:
Missouri - Mehl, 1960.
Rotschiefern:
Germany - Schriel and Stoppel, *1958a.
Sadler Formation:
Western Australia - Glenister, *1960; Glenister and Crespin, *1959.
Sappington Formation:
Montana - Gutschick, Suttner and Switek, 1962; Sandberg, 1962.
Saverton Shale:
Illinois - Scott, *1961; Collinson and Swann, 1958.
Missouri - Mehl, 1960; Howe and Koenig, 1961.
Upper Mississippi Valley - Collinson, Scott and Rexroad, 1962a, 1962b.
Sherburne Flagstone Member:
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.
Sonyea Formation - see Middlesex Shale Member and Parrish Limestone Bed of the Cashaqua Shale Member.
Sylamore Sandstone:
Illinois - Collinson and Swann, 1958.
Missouri - Mehl, 1960.
Oklahoma - Amsden, 1961.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959; Collinson, Scott and Rexroad, 1962a, 1962b.
Threeforks Shale:
Montana - Gutschick and Perry, 1959.
Turpin Sandstone Member of the Grassy Creek Shale:
Missouri - Mehl, 1960.
Unnamed formation:
Algeria - Remack-Petitot, *1960.
China - Ching, 1960.
France - Serre and Lys, *1960; Remack-Petitot, *1960.
Germany - Greiling, *1961; Hiltermann, 1961b; Kronberg, Pilger, Scherp, and Ziegler, *1960; Reichstein, *1959, 1960a, 1960b, 1961a; Schriel and Stoppel, 1960; Trautwein and Wittkindt, *1960.
Missouri - Echols, 1961.
Nevada - Dow, 1960.

Rio De Oro (Spanish Sahara) - Echols, 1963; Ethington and Furnish, *1962; Panseri, *1959.
Western Australia - Echols, 1963.
Wyoming - Ethington, Furnish, and Wingert, *1961; Koucky, Cygan, and Rhodes, *1961.

Unterer Alaunschiefer:
Germany - Helms, *1959b.

Unterer Kalkknollenschiefer:
Germany - Helms, *1959b.

Unterer Quarzitschiefer:
Germany - Schriel and Stoppel, *1958a.

Upper Bänderschiefer:
Germany - Klitzsch, *1959.

Varca - Ziet:
Germany - Krebs, *1959.

Virgin Hills Formation:
Western Australia - Glenister, *1960; Glenister and Crespin, 1959.

Wagner-Bank:
Germany - Helms, *1959b.

West Falls Formation - see Rhinestreet Shale Member.
New York - Hass, *1959b.
Pennsylvania - Hass, *1959b.

Wocklumeria (?) Stufe:
Spain - Ziegler, *1959b.

Woodford Shale:
Oklahoma - Amsden, 1960; Branson, 1959.

MISSISSIPPIAN (UNDIVIDED)

Tangpakou Limestone:
China - Ching, 1960.

Unnamed formation:
Algeria - Cuvillier, 1962a.
Indiana - Kesling, 1962.

LOWER MISSISSIPPIAN

Anchoralis-Stufe:
Germany - Voges, *1959b.

Aplington Formation:
Iowa - Echols, 1959.

Arkansas group - listed under Upper Devonian.

Arkansas Novaculite - listed under Upper Devonian.

Bachelor Formation:
Missouri - Mehl, 1960.

Banff Formation:
Alberta - Müller, 1962e.

Bedford Shale:
Ohio - Hoover, 1960.

Bohlen profils - listed under Upper Devonian.

Burlington Formation:
Illinois - Collinson and Swann, 1958.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.

Burt Range Limestone:
Northern Territory, Australia - Glenister, *1960.

Bushberg Formation:
Missouri - Mehl, 1960.

Castle Reef Dolomite:
Montana - Mudge, Sands and Dutro, 1962.

Cavusgnathus Beds:
Western Australia - Glenister, *1960.

Chappel Limestone:
Texas - Ellison, 1960; Gutschick, Weiner, and Young, 1961; Hass, 1959a.

Chattanooga Shale:
Mississippi River Valley - Weller, 1960.

Chouteau Limestone:
Illinois - Collinson and Swann, 1958.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959; Collinson, Scott and Rexroad, 1962a, 1962b.
Crenistria-Zone:
Germany - Voges, 1959b.
Cuivre Shale:
Missouri - Mehl, 1960.
Englewood Formation:
South Dakota - Klapper and Furnish, *1962.
English River Sandstone:
Upper Mississippi Valley - Collinson, Scott and Rexroad, 1962a, 1962b.
Fern Glen Limestone:
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962a, 1962b.
Gardner Formation:
Utah - Beach, *1961; Clark and Beach, 1962.
Glen Park Formation:
Illinois - Collinson, and Swann, 1958.
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962a; 1962b.
Grassy Creek Shale:
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Hangenbergkalk:
Germany Voges, *1959b; *1960.
Hannibal Shale:
Illinois - Collinson and Swann, 1958.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
Haupteruptionsphase der Deckdiabase:
Germany - Walliser, *1960b.
Keokuk Formation:
Illinois - Elias, 1959.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Kieselkalk:
Germany - Voges, 1959a; *1960.
Lake Valley Limestone:
New Mexico - Ash, 1962.
Laurel Beds:
Western Australia - Glenister, *1960.
Liegende Alaunschiefer:
Germany - Schriel and Stoppel, *1958a; Voges, *1959b; *1960.
Lodgepole Limestone:
Montana - Gutschick, Weiner, and Young, 1961.
Louisiana Limestone:
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
Lydite Kalk:
Germany - Voges, 1959a; *1960.
Madison Formation:
Wyoming - Kouchy, Cygan, and Rhodes, *1961.
New Albany Shale - listed under Upper Devonian.
Northview Formation:
Missouri - Echols, 1959.
Oberen Kalkknollenschiefer:
Germany - Helms, *1959b.
Obere Quarzitschiefer:
Germany - Schriel and Stoppel, *1958a.
Pahasapa Formation:
South Dakota - Klapper and Furnish, *1962.
Perapertu Formation:
Spain - Wagner and Wagner-Gentis, 1963.

Pericyclus - Stufe:
Germany - Krebs, *1960a.
Rockford Limestone:
Indiana - Gutschick, 1959.
St. Louis Formation:
Illinois - Collinson and Swann, 1958.
Salem Formation:
Illinois - Collinson and Swann, 1958.
Sappington Formation:
Montana - Gutschick, Suttner and Switek, 1962; Sandberg, 1962.
Saverton Shale:
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
Schiffelborner - Schichten:
Germany - Ziegler, 1959.
Sedalia Limestone:
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Septimus Limestone:
Western Australia - Glenister, *1960.
Siphonodella Zone:
Missouri - Mehl, 1960.
Springville Shale:
Illinois - Weller, 1960.
Spirit Hill Limestone:
Northern Territory, Australia - Glenister, *1960.
Tn_1b:
Belgium - Serre and Lys, *1960.
Tn_2a:
Belgium - Serre and Lys, *1960.
Tn_2b:
Beligum - Serre and Lys, *1960.
Tn_2b-c:
Belgium - Serre and Lys, *1960.
Unnamed formation:
Algeria - Remack-Petitot, *1960.
England - Mathews, 1961.
France - Remack-Petitot, *1960; Serre and Lys, *1960; Ziegler, *1959b.
Germany - Paproth, 1960; Trautwein and Wittekindt, *1960.
Missouri - Echols, 1961.
Utah - Sando, Dutro, and Gere, 1959.
Wechsellagerungen:
Germany - Schriel and Stoppel, *1958a.
Welden Limestone:
Oklahoma - Gutschick, Weiner, and Young, 1961.

UPPER MISSISSIPPIAN
Anchoralis-Stufe - listed under Lower Mississippian.
Arden Member Limestone and Shales:
Scotland - Clarke, *1960.
Assise de Warnant:
Belgium - Serre and Lys, *1960.
Barnett Shale:
Texas - Elias, 1959.
Beech Creek Limestone:
Illinois - Rexroad and Jarrell, *1961.
Indiana - Rexroad and Jarrell, *1961.
Kentucky - Rexroad and Jarrell, *1961.
Bilston Burn Bone Bed:
Scotland - Clarke, *1960.
Birkhead Beds:
Scotland - Clarke, *1960.
Blackhall Limestone and Shales:
Scotland, Clarke, *1960.

Bluefield Shale:
Virginia - Rexroad and Clarke, *1960.
Bluefield Group:
West Virginia - Rexroad and Clarke, *1960.
Brazer Limestone:
Idaho - Skipp, 1961.
Calcaire à Polypiers de Temploux:
Belgium - Serre and Lys, *1960.
Caney Shale - see Sand Branch Member.
Castlecary Limestone and Shales:
Scotland - Clarke, *1960.
Clore Limestone:
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Cove Creek Limestone:
Virginia - Rexroad and Clarke, *1960.
Delaware Creek Shale:
Oklahoma - Elias, 1959; Elias and Branson, 1959.
Downeys Bluff Formation:
Illinois - Rexroad and Liebe, *1962.
Kentucky - Rexroad and Liebe, *1962.
Erdbacherkalk Horizont:
Germany - Voges, *1959b.
Fraileys Shale:
Illinois - Rexroad and Jarrell, *1961.
Glencart Beds:
Scotland - Clarke, *1960.
Glen Dean Limestone:
Illinois - Elias, 1959.
Kentucky - Rexroad and Clarke, *1960.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Goddard Shale:
Oklahoma - Elias, 1959.
Golconda Formation:
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
"Griotte" Limestone:
Spain - Higgins, 1962.
Haney Limestone:
Illinois - Rexroad and Jarrell, *1961.
Indiana - Rexroad and Jarrell, *1961.
Kentucky - Rexroad and Jarrell, *1961.
Hawthorn Limestone:
Scotland - Clarke, *1960.
Heath Formation:
Montana - Willis, 1959.
Helms Formation:
Texas - Ellison, 1962a.
Hurlet Limestone and Shales:
Scotland - Clarke, *1960.
Index Limestone and Shales:
Scotland - Clarke, *1960.
Johns Valley Shale:
Oklahoma - Cline, 1960; Elias and Branson, *1959.
Kinkaid Limestone:
Illinois - Rexroad and Burton, *1961.
Kulmkieselschiefer:
Germany - Schriel and Stoppel, *1958a.
Law Beds:
Scotland - Clarke, *1960.
Linn Spout Beds:
Scotland - Clarke, *1960.
Lower Limestone Group:
Scotland - Clarke, *1960.

Maxville Limestone:
Ohio - Kesling, 1961; 1963.
Menard Limestone:
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Millstone Grit:
Scotland - Clarke, *1960.
Monkcastle Beds:
Scotland - Clarke, *1960.
North Greens Limestone and Shales:
Scotland - Clarke, *1960.
Paint Creek Formation:
Illinois - Elias, 1959.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Paoli Formation:
Indiana - Rexroad and Liebe, *1962.
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959.
Pella Limestone:
Iowa - Dow, 1960.
Oklahoma - Elias, 1959.
Pericyclus - Stufe:
Germany - Walliser, *1959.
Petershill Limestone and Shales:
Scotland - Clarke, *1960.
Ponniel Water Bed:
Scotland - Clarke, *1960.
Posidonienkalk:
Germany - Meischner, *1962.
Renault Formation:
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
Rhenaer Kalk:
Germany - Meischner, *1962.
Ste. Genevive Limestone:
Illinois - Collinson and Swann, 1958.
Kansas - Thompson and Goebel, *1963.
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
St. Louis Limestone:
Kansas - Thompson and Goebel, *1963.
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott, and Rexroad, 1962b.
Salem Formation:
Kansas - Thompson and Goebel, *1963.
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Rexroad and Scott, 1962b.
Sand Branch Member of the Caney Shale:
Oklahoma - Elias and Branson, *1959.
Second Abden Limestone and Shale:
Scotland - Clarke, *1960.
Shetlerville Member of the Renault Formation:
Illinois - Rexroad and Liebe, *1962.
Kentucky - Rexroad and Liebe, *1962.
Skateraw Middle Limestone and Shales:
Scotland - Clarke, *1960.
Stacklawhill Beds:
Scotland - Clarke, 1960.
Stanley Shale:
Oklahoma - Cline, 1960; Elias, 1959; Shelburne, 1960.
Tesnus Formation:
Texas - Ellison, 1962a.
Top Hosie Limestone and Shales:
Scotland - Clarke, *1960.

Unnamed formation:
Algeria - Remack-Petitot, *1960.
France - Remack-Petitot, *1960; Serre and Lys, *1960.
Germany - Paproth, 1960; Ziegler, *1960b.
Spain - Ziegler, *1959b.
Upper Limestone Group:
Scotland - Clarke, *1960.
V_3b:
Belgium - Serre and Lys, *1960.
V_3:
Belgium - Serre and Lys, *1960.
Vienna Limestone:
Upper Mississippi River Valley - Collinson, Rexroad, and Scott, 1959. Collinson, Scott and Rexroad, *1962b.
Warsaw Formation:
Kansas - Thompson and Goebel, *1963.
Upper Mississippi Valley - Collinson, Rexroad and Scott, 1959; Collinson, Scott and Rexroad, 1962b.
Wesley Formation:
Oklahoma - Cline, 1960.
Winterberg:
Germany - Helms, 1960b.
Yankeetown Formation:
Illinois - Rexroad and Liebe, *1962.
Kentucky - Rexroad and Liebe, *1962.

PENNSYLVANIAN (UNDIVIDED)
Gap Tank Formation:
Texas - Ellison, 1962a.
Madera Limestone:
New Mexico - Ash, 1962.
Magdalena Group:
New Mexico - Ash, 1962.
Texas - Ellison, 1962a.
Minturn Limestone:
Colorado - Anderson, 1962.
Naco Limestone:
Arizona - Ash, 1962.
Unnamed formation:
Brazil - Lange, 1961.
China - Ching, 1960.
Kansas - Echols, 1959.
Missouri - Echols, 1959.

LOWER PENNSYLVANIAN
Amsden Formation:
Wyoming - Koucky, Cygan, and Rhodes, *1961.
Chickasaw Creek Formation:
Oklahoma - Cline, 1960.
Glen Eyrie Shale:
Colorado - Lehmann, 1953.
Skipsey's Marine Band:
Scotland - Clarke, *1960.
Springer Formation:
Oklahoma - Elias, 1959.
Unnamed formation:
Algeria - Remack-Petitot, *1960.

MIDDLE PENNSYLVANIAN
Amsden Formation - listed under Lower Pennsylvanian.
Cherokee Shale:
Kansas - Mamay and Yochelson, *1962.
Dorr Run Member of the Lower Freeport Cyclothem:
Ohio - Sturgeon, 1958.

Fort Scott Formation:
Missouri - Unklesbay, *1952.
Krebs Group:
Oklahoma - Mamay and Yochelson, *1962.
Lake Neosho Shale:
Iowa - Kesling, 1961.
Kansas - Kesling, 1961.
Missouri - Kesling, 1961.
McLeansboro Group:
Illinois - Mamay and Yochelson, *1962.
Paradox Formation:
Colorado - Elias, G. K., 1963.
Utah - Elias, G. K., 1963; Jones, 1960.
Staunton Formation:
Indiana - St. Jean, 1957.
Tebo Formation:
Missouri - Unklesbay, *1952.
Unnamed formation:
Algeria - Remack-Petitot, *1960.
Iowa - Dow, 1960.

UPPER PENNSYLVANIAN
Ames Limestone Member of the Conemaugh Series:
Ohio - Sturgeon, 1958.
Dennis Formation - see Stark Shale Member.
Eudora Shale Member of the Stanton Limestone:
Kansas - Ball, *1959; Ball, Ball and Laughlin, *1963.
Gaysport Limestone Member of the Gaysport Cyclothem:
Ohio - Sturgeon, 1958.
Heebner Shale Member of the Oread Formation:
Iowa - Welp, Thomas and Dixon, 1957.
Kansas - Ball, 1959; Ball, Ball, and Laughlin, *1963.
Hushpuckney Shale Member of the Swope Formation:
Iowa - Welp, Thomas, and Dixon, 1957.
Minnelusa Formation:
South Dakota - Jennings, *1959.
Modesto Formation:
Illinois - Kosanke, Simon, Wanless, and Willman, 1960.
Oread Formation - see Heebner Shale Member.
Quindaro Shale Member of the Wyandotte Formation:
Iowa - Welp, Thomas, and Dixon, 1957.
Stark Shale Member of the Dennis Formation:
Iowa - Welp, Thomas, and Dixon, 1957.
Swope Formation - see Hushpuckney Shale Member.
Winterset Formation:
Iowa - Dow, 1960.
Wyandotte Formation - see Quindaro Shale Member.

LOWER PERMIAN
Beattie Limestone - see Florena Shale Member.
Bone Springs Formation:
Texas - Clark and Ethington, *1962.
Cherry Canyon Formation - see Getaway Member.
Florena Shale Member of the Beattie Limestone:
Kansas - Verville, 1958.
Foraker Limestone - see Hughes Creek Shale Member.
Getaway Member of the Cherry Canyon Formation:
Texas - Ash, 1962; Sohn, *1961.
Hughes Creek Shale Member of the Foraker Limestone:
Kansas - Verville, 1958.
Kufeng Suite (Formation):
China - Ching, *1960.
Meade Peak Phosphatic Member of the Phosphoria Formation:
Idaho - Clark and Ethington, *1962; McKelvey and others, *1959.

Montana - McKelvey and others, *1959.
Utah - McKelvey and others, *1959.
Wyoming - MeKelvey and others, *1959.
Phosphoria Formation - see Meade Peak Phosphatic Shale Member.
San Andres Limestone:
New Mexico - Ash, 1962; Clark and Ethington, *1962.
Siksikpuk Formation:
Alaska - Bergquist, *1960.
Tensleep Sandstone:
Wyoming - Rhodes, 1963.
Unnamed Formation:
Arizona - Clark and Ethington, *1962.
Mexico - Clark and Ethington, *1962.
Werra - Dolomit:
Germany - Seidel, 1959.
Wolfcamp Formation:
Texas - Ellison, 1962a.

LOWER TRIASSIC
Gondolella planata Assemblage Zone:
Nevada - Clark, 1960.
Meekoceras limestones:
Nevada - Clark, *1959.
Utah - Clark, *1959.
Meekoceras zone of the Thaynes Limestone:
Nevada - Jones, *1960.
Utah - Jones, *1960.
Neoprioniodus bransoni Assemblage Zone:
Nevada - Clark, 1960.
Thaynes Limestone:
Nevada - Schell and Clark, 1960.
Also see *Meekoceras* zone.
Unnamed formations:
Nevada - Clark, *1959.
Utah - Clark, *1959.

MIDDLE TRIASSIC
Asklepieionkalk:
Greece - Bender, *1960.
Dachsteinkalk:
Austria - Zankl, *1962.
Knubbelkalk:
Austria - Huckriede, *1959a.
Oberen Muschelkalk:
Germany - Hirschmann, *1959.
Shublik Formation:
Alaska - Bergquist, 1960.
Unnamed formation:
Bulgaria - Budurov, *1960; Stefanov, *1962.
Nevada - Anderson, 1962.

UPPER TRIASSIC
Asklepieionkalk - listed under Middle Triassic.
Rot-und Graukalksteinen:
Bulgaria - Budurov, *1959.
Shublik Formation - listed under Middle Triassic.
Unnamed formation:
Bulgaria - Spasov and Ganev, *1960.
Zone von *Trachiceras aonoides*:
Bulgaria - Budurov, *1959.

STRATIGRAPHIC AND GEOGRAPHIC DISTRIBUTION OF CONODONT-BEARING ROCKS

The reported stratigraphic and geographic distribution of conodont-bearing rocks is summarized in Table 1. Published articles which mention conodont-bearing rocks of a certain geologic system in a particular geographic area can be located by referring to Table 1 and to the geologic indexes and accompanying bibliographies in the Catalogue of conodonts (Fay, 1952), in my previous bibliography and index of conodonts (1961), and in this paper.

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TABLE 1 — CONODONT OCCURRENCE

F, occurrence reported in Catalogue of conodonts (Fay, 1952); Al, occurrence reported in Bibliography and index of conodonts, 1949-1958 (Ash, 1961); A2, occurrence reported in this paper.

COUNTRY	GEOLOGIC SYSTEM AND ERA	PALEOZOIC							MESOZOIC		
						CARBONIFEROUS					
		CAMBRIAN	ORDOVICIAN	SILURIAN	DEVONIAN	MISSISSIPPIAN	PENNSYLVANIAN	PERMIAN	TRIASSIC	JURASSIC	CRETACEOUS
AFRICA											
Algeria				A1, A2	A1, A2	A1, A2	A2				
Cameroons											A1
Egypt						F, A1	F, A1		F, A1		
Rio de Oro					A2						
ASIA											
China					A2	A2	A2				
Pakistan (west)									A1		
Palestine									A1		
Turkey					A1				A1		
AUSTRALIA											
Northern Territory			F, A1		A2	A2					
Queensland		A2									
Western Australia			A1, A2	A1, A2	A1, A2	A1, A2					
EUROPE											
Austria					A1	A1			A1, A2		
Baltic region			F								
Belgium					A2	F, A2					
Bulgaria				A2					A2		
Czechoslovakia			F	F							
Estonia			F, A1	F, A2							
France					A1, A2	A1, A2					

TABLE 1 (CONT'D.)

Germany	A1, A2	A1	F, A1, A2	F, A1, A2	F, A1, A2	A1	F, A1, A2	F, A1, A2		
Great Britain										
England		A1, A2	F, A1, A2	A1, A2	F, A1, A2	F, A1				
Northern Ireland					A1	A1				
Scotland		F, A1			F, A1, A2	F, A1, A2				
Greece								A1, A2		
Italy				A1				A1		
Netherlands						A1				
Poland		A2		F						
Prussia			F							
Russia		F, A2		F	F					
Sicily							A1			
Silesia		F		A1						
Spain			A1, A2	A1, A2	A1, A2					
Sweden	A2	F, A1, A2								
Yugoslavia			A2					A2		
NORTH AMERICA										
Canada										
Alberta				F, A1	F, A2					
British Columbia		A2								
Mackenzie region				F						
Manitoba		A2								
Northwest Territories		A2	A2							
Ontario		F, A2		F, A1						
Quebec		F								
Mexico										
Chihuahua		A2		A2						
Coahuila							A2			
United States of Amer.										
Alabama		A2		F, A1	A1					
Alaska							A2 (?)	A2		
Arizona				A1, A2			A2			
Arkansas			A2	F, A1	F, A1	A1				
Cincinnati arch				A1						
Colorado		F, A1, A2		A1		F, A1, A2				

TABLE 1 (CONT'D.)

Idaho					A2		A1, A2	A1		
Illinois		A1	A1, A2	F, A1, A2	F, A1, A2	F, A1, A2				
Indiana		A1, A2	F	F	F, A1, A2	F, A1, A2				
Iowa		F, A1, A2	F, A1	F, A1, A2	F, A1, A2	F, A1, A2				
Kansas					F, A2	F, A1, A2	F, A1, A2			
Kentucky		F, A1, A2	F	F	F, A1, A2	A1, A2				
Maine		A2								
Maryland				F						
Michigan		A1		F, A1	A1					
Minnesota		F, A1, A2		F						
Mississippi				F, A1	A1					
Mississippi Valley		A1		A1, A2	A1, A2					
Missouri		F, A1, A2	F, A1	F, A1, A2	F, A1, A2	F, A1, A2				
Montana		A1		F, A1, A2	F, A1, A2	F, A1	A2			
Nebraska						A1	F			
Nevada	A2	A1, A2		A1, A2				A1, A2		
New Jersey		A1								
New Mexico				A1, A2	A2	A1, A2	A1, A2			
New York		F, A1		F, A1, A2						
North Dakota		F, A1, A2			F	F				
Ohio		F, A1, A2		F, A1, A2	F, A1, A2	F, A1, A2				
Oklahoma	A1, A2	F, A1, A2	F, A1, A2	F, A1, A2	F, A1, A2	F, A1				
Pennsylvania		F, A1		A1, A2						
South Dakota	A1, A2	F, A1, A2		A2	A2	A2				
Tennessee		F, A1		F, A1, A2	F, A1					
Texas	A2	F, A1, A2	F, A1	F, A1, A2	F, A1, A2	F, A1, A2	A2			
Utah	A1, A2			A2	A2	F, A1, A2	A2	A1, A2		
Virginia				F	A2					
Washington					A1					
West Virginia					A2					
Wisconsin				F						
Wyoming	A1, A2	F, A1, A2		F, A1, A2	F, A2	F, A2	F, A2			
SOUTH AMERICA										
Argentina		A1								
Brazil						A2				

Orthoquartzites of the Oquirrh Formations*

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ABSTRACT.—The Oquirrh Formation of Pennsylvanian and Wolfcampian Permian age in the Oquirrh Basin of northwest central Utah consists mainly of calcareous and siliceous clastic sedimentary rocks. A thickness of 15,540 feet of Oquirrh Formation was measured at South Mountain west of Stockton in Tooele County, Utah, consisting prineipally of orthoquartzite, calcareous and calcarenaceous orthoquartzite, and siliceous quartz sandstone, with minor cherty limestone and calcarenite. Approximately 7,250 feet of Wolfcampian age Oquirrh rocks is exposed in Hobble Creek Canyon east of Springville, Utah and is of similar lithology. The Wolfcampian interval of the Weber Formation exposed in Weber Canyon consists of 714 feet, of which, approximately 80 percent is orthoquartzite, none of which is calcareous.

Orthoquartzites of the Oquirrh Formation constitute a unique suite of sedimentary rocks, deposited in shallow water in a large marine basin which was subject to irregular instability and deep subsidence. Clastic sediments in the Oquirrh Formation were eroded from local positive areas peripheral to the Oquirrh Basin, and contributed to the basin through various accessways. These sediments are fairly well sorted and generally subrounded to subangular, equant, anhedral grains. Much of the quartz was derived from pre-existing sedimentary rocks.

A study of orthoquartzites from approximately thirty other formations in the United States failed to reveal any other examples of calcarenaceous orthoquartzite such as found in the Oquirrh Formation, but did reveal certain characteristic aspects of orthoquartzite petrography. Orthoquartzites in general are non-porous, light colored rocks consisting of 95% or more anhedral quartz grains, in which silica cementation has taken place through pressure solution or by addition of new silica, or both.

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ILLUSTRATIONS

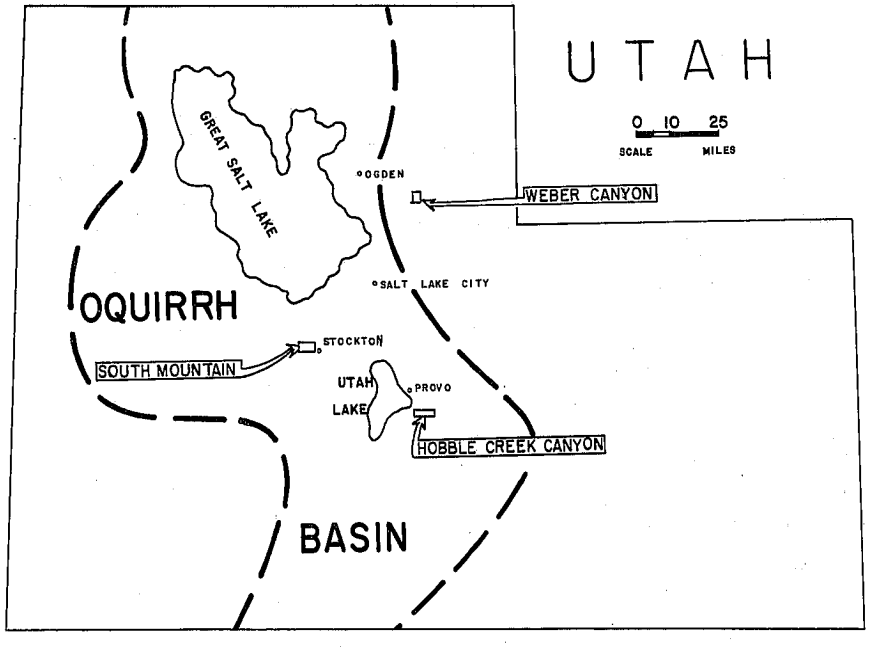
*A thesis submitted to the Faculty of the Department of Geology, Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science.

CONTENTS (CONT.)

INTRODUCTION

This report is concerned with the petrology and petrography of some clastic sedimentary rocks of the Oquirrh and Weber Formations of Pennsylvanian and Permian ages. Stratigraphic sections were studied and sampled at South Mountain in Tooele County, Utah, Hobble Creek Canyon in Utah County Utah, and Weber Canyon in Morgan County, Utah (Text-fig. 1).

The Oquirrh Formation is an unusually thick miogeosynclinal sequence of calcareous and clastic sedimentary rocks ranging from Morrowan (Early Pennsylvanian) through Wolfcampian (Early Permian) age in central and northern Utah and southern Idaho. The Oquirrh Formation lies conformably on the Manning Canyon Formation of late Mississippian and early Pennsylvanian age, except in the Stansbury Mountains, where the contact is an angular un-



TEXT-FIGURE 1. Index map of the Oquirrh Basin showing location of sections.

conformity (Wright, 1961, p. 166). The Oquirrh Formation is conformably overlain by Wolfcampian age limestones of the Kirkman Formation (Bissell, 1962a, p. 34).

The Weber Formation is essentially the stable shelf equivalent of the Oquirrh Formation in northeastern Utah and northwestern Colorado. It is largely an unfossiliferous series of sandstone and orthoquartzite with a few interbedded limestone units, and ranges in age from Desmoinesian (late Medial Pennsylvanian) to Wolfcampian. It is 2260 feet thick at its type locality near Morgan in Weber Canyon. The Weber thins gradually eastward to about 1000 feet at the Colorado border, and eventually interfingers with the Maroon Formation to the east (Bissell and Childs, 1958, p. 26). The Weber disconformably overlies Pennsylvanian limestones and shales of the Morgan Formation, and is disconformably overlain by the Permian Park City-Phosphoria Formations.

Purpose

This study is primarily an investigation of the orthoquartzites of the Oquirrh Basin, undertaken to clarify and revise classification and nomenclature of these clastic sedimentary rocks, and to aid evaluation of the geologic history of the Oquirrh Basin and contiguous shelf areas. This is part of a continuing study of this unique geologic region by various faculty members and graduate students in the Geology Department of Brigham Young University (Bissell, 1936, 1959a, 1959b, 1960, 1962a, 1962b; Croft, 1956; Hodgkinson, 1961; Moyle, 1958; Rigby, 1958; and Wright, 1961).

Procedure

Methods applied in this investigation include standard megascopic petrologic examination, description, measurement, and sampling of the strata involved, observation of stratigraphic relationships such as lateral variations, directions of thickening or thinning, nature of contacts, and lithologic variations, petrographic analysis of 66 thin sections, including samples of each rock type from each locality, insoluble residue study of the calcareous samples, and comparison of the orthoquartzites of the Oquirrh and Weber Formations with sandstones and quartzites from other formations. Because of the objectives of the study, greater effort was devoted to investigation of the orthoquartzites than to the other rocks in the section, both in the field and in the laboratory.

Field work was begun in February, 1962, and continued through June 1962. Thickness of the South Mountain section was obtained by means of steel tape and Brunton compass. Laboratory and petrographic work was done in the Geology Department of Brigham Young University. Location of the Pennsylvanian-Permian boundary in all the sections is based on faunal studies by Bissell and others.

Acknowledgments

The writer wishes to express sincere gratitude to his Thesis Advisory Committee, composed of Dr. J. R. Bushman, chairman, Dr. H. J. Bissell, and Dr. J. K. Rigby. Field assistance was furnished by William E. Sweet, Monte Wilson, and R. Dean Rasmussen. Dr. Hugh W. Dresser of the Humble Oil and Refining Company generously provided facilities and equipment for taking the photomicrographs. Advice and encouragement was given by various graduate students in the Geology Department of Brigham Young University, and by various members of the Casper District Exploration Office of the

Humble Oil and Refining Company. Ideas presented in this report are not to be construed as official opinions of the Humble Oil and Refining Company.

Previous Investigation

The first published reference to what is now known as the Oquirrh Formation was by J. E. Spurr in his 1895 report on the geology of the Mercur Mining District, in the southwestern part of the Oquirrh Range. The name "Oquirrh" was first used by Keyes (1924, p. 37) for 500 feet of "quartzite" at the base of his "Weberian" series. Nolan (1930) applied the name "Oquirrh" to Pennsylvanian rocks lithologically similar to the Oquirrh Formation of present usage in the Gold Hill Mining District in far western Tooele County. Gilluly (1932) gave formal definition to the Oquirrh Formation, and established a type locality in the Oquirrh Mountains, immediately west of Salt Lake Valley and east of Tooele Valley and Rush Valley. The first successful attempt at subdivision and faunal zonation within the Oquirrh Formation was the fusulinid work of Bissell (1936). In later reports Bissell (1959a, 1959b, 1960, 1962a, 1962b) has discussed the distribution, sedimentation, tectonics, and biostratigraphy of the Oquirrh and other Upper Paleozoic formations in western Utah, eastern Nevada, and southern Idaho. Another important fusulinid study was done by Thompson, Verville, and Bissell in 1950.

Baker (1947) published a description of the stratigraphy of the southern Wasatch Mountains, including two stratigraphic sections of the Oquirrh Formation. In that report, he confirmed the presence of Wolfcampian strata within the formation.

Wright (1961) discussed stratigraphy and tectonic setting of the Oquirrh Formation in the Stansbury Mountains, which lie to the west of Tooele Valley and Rush Valley.

Welsh and James (1961 p. 1-16) proposed the advancement of the Oquirrh Formation to group rank, restriction of the name to Pennsylvanian strata, and subdivided it into four formations with eighteen members. These changes have not been generally adopted, and are not herein recommended because of their apparent local utility. Tooker and Roberts, in the same guidebook, (1961 p. 17-26) mapped seven units of the Oquirrh Formation, five Pennsylvanian and two Permian, in the northern Oquirrh Mountains.

Terminology

In any dynamic science such as geology certain terms have been given various meanings by different authors. The following is a list of terms as used in this paper, which, in general, follows nomenclature advocated by Dunbar and Rodgers (1958, p. 165-167).

Terms

Sandstone.—Any clastic sedimentary rock composed predominantly of sand size grains (mean diameter between 2.0 and 1/16 mm) of quartz and silicate minerals.

Siltstone.—As above, except that the majority of grains are in the silt size range (1/16 to 1/256 mm). If the rock is sufficiently well cemented with silica that it breaks with an intragranular fracture, the term "silicasiltite" may be

applied. In field examination of silica cemented rocks grain size is often obscured by cement, the more general terms quartzite, orthoquartzite, or metaquartzite are applicable.

Quartzite.—A rock composed principally of sand and/or silt size quartz grains cemented by silica. Because of the equal tenacity of the grains and the cement, the rock fractures with a general intragranular fracture. Traditionally, the term quartzite has indicated a metamorphic rock, although such a rock can result from strictly non-metamorphic processes.

Orthoquartzite.—A sedimentary quartzite in which the silica cement is diagenetic or authigenic and not a product of metamorphism. Cementation has occurred at a pressure and temperature below that of metamorphism, either by filling voids or replacement of primary cement by secondary silica. These rocks also display characteristic intragranular fracture and, at least megascopically, closely resemble metaquartzites.

An alternate meaning for the term orthoquartzite has been proposed (Krynine, 1948, p. 149-152). Krynine would apply the terms quartzite or orthoquartzite to any sandstone in which the clastic fraction is quartz and chert and the cement is at least 50% silica, regardless of the amount of cement or the degree of compaction. This usage has been accepted by certain authors. (Siever, 1960, p. 182; Folk, 1961, personal communication) and rejected by others (Dunbar and Rodgers, 1958, p. 165; Gilbert, in Williams, Turner, and Gilbert, 1954; American Geological Institute, 1957). As a result, ambiguity in use of this term is common in geologic literature.

Metaquartzite.—A quartzite of unquestioned metamorphic origin, as evidenced by presence of characteristic metamorphic minerals, micaceous minerals arranged in foliation planes, or an overlying sequence of metamorphic rocks in normal contact. Metaquartzites can seldom be distinguished from orthoquartzites in hand samples, and thus arises utility of the term quartzite, which may be applied to both varieties.

Prefixes

The term "quartz" may be used as a prefix to indicate at least 90% of the detrital fraction of a clastic sedimentary rock is composed of quartz, including chert, chalcedony, and quartzite or sandstone fragments.

Qualifying adjectives such as "siliceous," "calcareous," "dolomitic," etc., indicate mineral cement or matrix present in subordinate amounts. Thus, a "calcarenaceous orthoquartzite" is a consolidated aggregate of quartz grains, cemented by silica, containing detrital calcite sand or silt.

"Calcareous" is mainly a field term applied to those rocks which readily react with dilute hydrochloric acid, whereas the term "calcarenaceous" is applied to those rocks in which calcite is in detrital grains.

Because the calcarenaceous orthoquartzites in the Oquirrh Formation are often obviously clastic, and usually develop a dense, non-calcareous, siliceous weathering rind, and yet will readily effervesce when dilute acid is applied to a fresh exposure, they have been called by a wide variety of names. For example, the Wolfcampian part of the Oquirrh Formation, which is made up largely of this rock type, has been referred to as limestone, sandy limestone, sandstone, quartzite, orthoquartzite, and calcareous orthoquartzite. Such variability in petrologic nomenclature is at best misleading, and as a result con-

struction of meaningful clastic ratio maps, sandstone isoliths and isopachs, and lithofacies maps is impossible.

OQUIRRH BASIN STUDY

South Mountain Section

The entire exposure of Oquirrh Formation at South Mountain (T. 4 S., R. 5 and 6 W.), west of Stockton in Tooele County, Utah, was measured, described, and sampled. South Mountain contains a broad, northwest plunging anticline with overturned strata on the nose of the fold. Approximately 15,540 feet of Oquirrh strata is exposed here, ranging from Morrowan through Wolfcampian ages, based on fusulinid studies by Welsh and James (1961, p. 7) and Bissell (1962, personal communication). The Wolfcampian portion of the Oquirrh Formation is 9,410 feet thick.

The underlying Manning Canyon Shale is not exposed, but the contact with the overlying Wolfcampian Kirkman Formation is at the base of the west slope of the western summit of South Mountain. The measured section is shown graphically in text-figure 2, and the relative proportion of rock types present is given in table 1.

The following rock types were observed in the Oquirrh Formation at South Mountain:

Calcarenite.—Units 1, 2, 7, and 8 are gray to dark gray, clastic limestones composed mainly of detrital calcite grains and skeletal material in a matrix of micrite or fine calcitic mud (Pl. 1, fig. 1). This calcarenite ranges from 73% to 98% carbonate, and the insoluble residue contains silt, clay, silica, and various skeletal fragments.

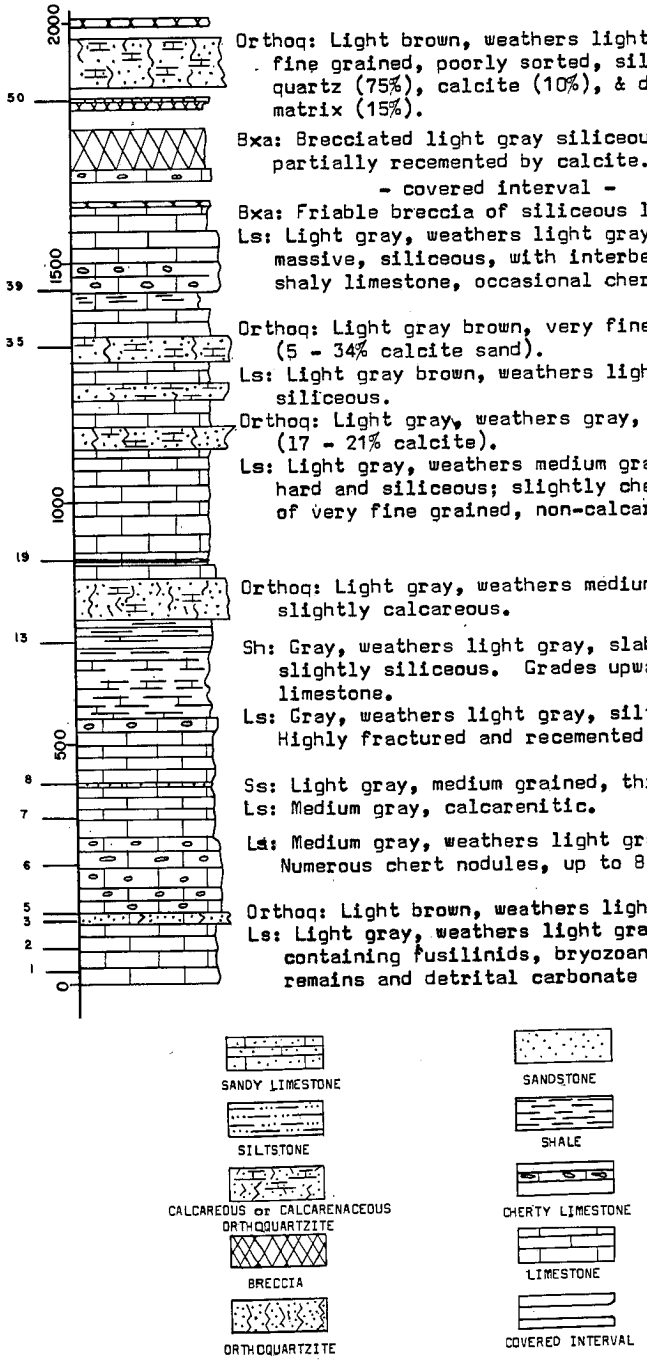
Cherty limestone.—Units 6, 39, and 78 are medium gray, light gray weathering, aphanic to slightly silty, siliceous limestones which contain nodules and stringers of massive, concretionary, and bedded gray to brown chert in discontinuous and irregular distribution. The largest chert nodule was observed in unit six, and measured slightly more than eight feet across. Dissolved samples of these cherty limestones indicated 7% to 88% carbonate, and yielded a residue of angular fragments of dense, vitreous, dark gray to black chert.

Shale.—Units 13 and 79 are gray, calcareous, platy shales which weather a light brown color and commonly split into quarter-inch laminae. Also present are some gray, highly argillaceous, platy limestones which are gradational with the shale.

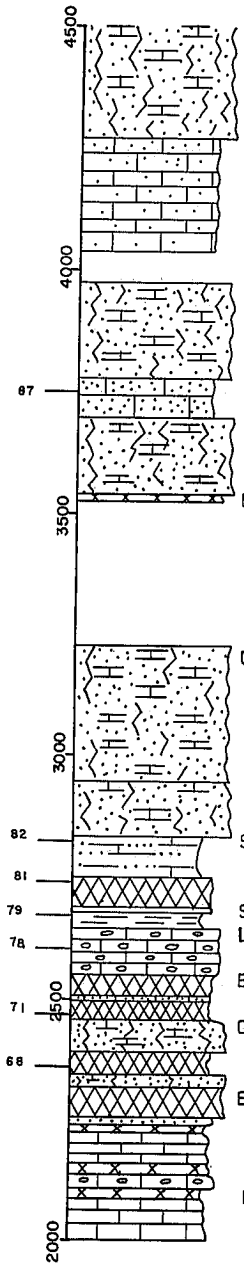
Quartz sandstone.—Units 91 and 130 are light gray to light brown, friable, non-calcareous rocks composed of very fine grained quartz sand and silt, partially cemented with silica or calcite. A typical sample of this sandstone consists of 97% quartz, 1% clay, and 1% cement, with traces of microcline, detrital chalcedony, and heavy minerals. The sand ranges from very fine to silt size, and grains are well sorted, sub-rounded to well rounded, anhedral and equant. Grain boundaries are rough and quartz grains are occasionally intergrown (Pl. 1, fig. 2).

Siliceous quartz sandstone.—As above, but with an increase in silica cement, resulting in increased tenacity, but still with a tendency to break around rather

TEXT-FIGURE 2. Columnar section of the Oquirrh Formation exposed at South Mountain (T. 4 S., R. 5 W.) Tooele County, Utah. Numbers in lefthand margin indicate location of samples mentioned in text.



(TEXT-FIG. 2, CONT.)



Orthoq: Light gray, weathers light brown, very fine grained to silty, slightly calcareous.

Ls: Light gray, sandy/silty, partially covered. Insoluble residue contains sand, silt, light gray clay, and quartzite rock fragments.

Ss: Light brown, weathers light gray, very fine grained to silt size grains, matrix of granular calcite silt, (37% calcite), trace of silica cement. Grades upward into calcareous orthoquartzite as silica cement increases.

Bxa: Zone of brecciated orthoquartzite at top of covered interval.

- covered interval -

Orthoq: Light brown, weathers very light brown, hard, dense, highly jointed, 12% calcite. Quartz grains form an interlocking mosaic in which the original grain shape is obscured pressure solution and silica cementation.

Slst: Light gray, calcite cemented quartz silt, 10% calcite.

Sh: Light gray, calcareous, grades into shaly limestone.

Ls: Light gray, weathers very light gray, micritic, cherty, ledge former; contains fossil corals.

Bxa: Light brown brecciated orthoquartzite, calcite cemented.

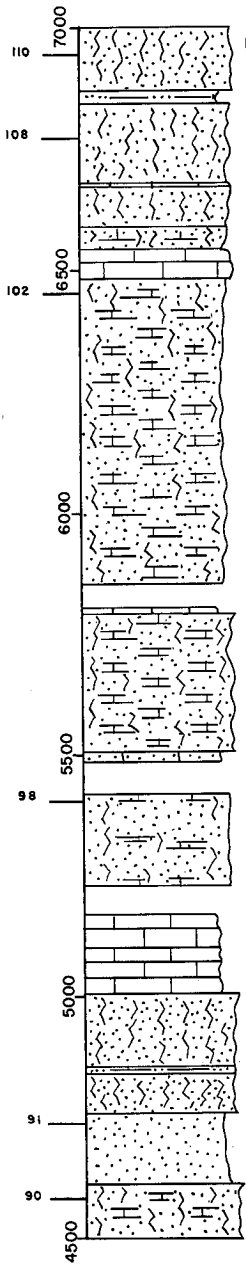
Orthoq: Light gray to light brown, very fine grained to silt size grains, 5 to 10% calcite silt matrix.

Bxa: Light brown, siliceous, ledge former.

Ss: Light brown, very fine grained to silty, poorly sorted, slightly siliceous.

Bxa: Light brown, light gray weathering, friable, calcite cemented breccia of siliceous limestone & orthoquartzite.

(TEXT-FIG. 2, CONT.)



Orthoq: Light brown, silty, alternating layers of sub-angular very fine grained quartz sand and well rounded medium grained quartz sand; non-calcareous.

Ls: Light gray, weathers very light gray with mottled light brown stain, thin bedded, micritic to slightly sandy texture. Fossil "worm trails" near top.

Orthoq: Light gray, weathers very light brown, very fine grained, massive, calcarenaceous (10% calcite), trace of detrital microcline. Weathers into ½" slabs.

Orthoq: as above

Ss: Light gray brown, weathers light brown, fine to very fine grained, slightly siliceous, calcareous.

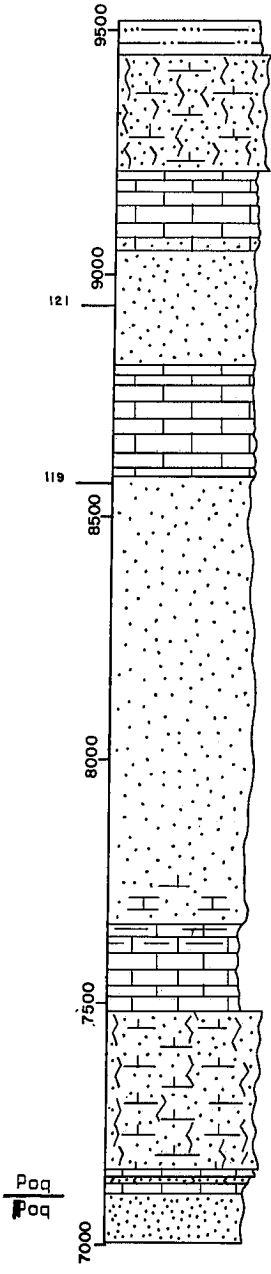
Ls: Very dark gray, weathers medium gray, hard, dense, siliceous.

Orthoq: Light gray brown, weathers very light brown, fine grained, massive, non-calcareous, well cemented. Trace of porosity as isolated silt size voids.

Ss: Very light brown, very fine grained, massive, highly weathered, non-calcareous, slightly porous. Grains are 99% well sorted, anhedral, equant, interlocking quartz; trace of microcline, chalcedony, clay.

Orthoq: Light gray, weathers light brown, very fine grained, slightly calcareous.

(TEXT-FIG. 2, CONT.)



Slst: Light gray, weathers light brown, calcite cemented quartz siltstone.

Orthoq: Light gray, weathers light brown, silt size silica cemented quartz grains, calcareous matrix. Dense & non-porous; breaks with smooth intragranular fracture.

Ls: Light gray, weathers light brown, massive to slightly silty. Contains fossil "worm trails".

Ss: Light brown, weathers light gray, very fine grained & silty, well bedded, partially cemented by silica; Trace of porosity. Original shape of sand grains is obscured by secondary quartz overgrowths.

Ls: Medium gray, weathers light gray, slightly silty, dense, massive, non-porous.

Ss: Light gray, weathers pinkish gray, fine to very fine grained with trace of siliceous cement. Grains are quartz 95%, chalcedony 3%, detrital calcite 2%; 5% clay matrix, up to 5% porosity, trace of hematite. Quartz intergrowths are common. This type may be the weathered/leached equivalent of the calcareous/ calcarenaceous orthoquartzite.

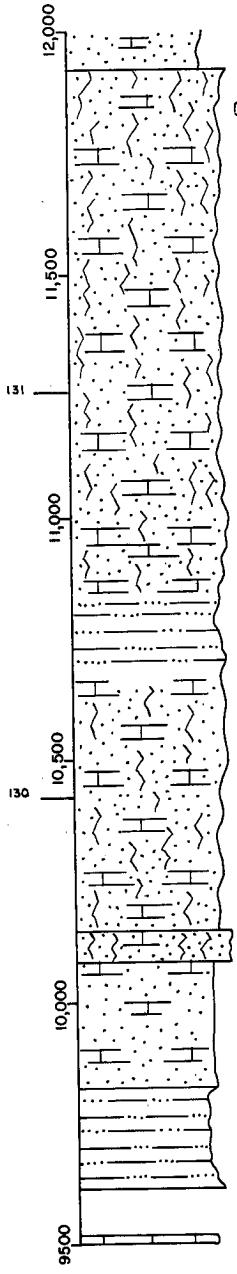
Ss: Light gray, very fine grained, silty, calcite cemented. Weathers to friable, light brown, non-calcareous sandstone.

Ls: Very dark gray to black, weathers light gray, silty & argillaceous, thin undulatory bedding, becomes fissile at top.

Orthoq: Dark to medium gray, weathers light brown, very fine to silt size quartz sand, 15% calcite silt. Gradational change to overlying silty, siliceous limestone.

Ls: Light gray, weathers light brown, slightly silty siliceous calcilutite.

(TEXT-FIG. 2, CONT.)



Orthoq: Light gray brown, weathers light brown; predominantly very fine grained with occasional beds of fine grained sand and silt, with matrix of detrital calcite silt (13% calcite). Cement is mainly silica, with some calcite. Sand fraction is 97% quartz, with minor microcline and calcite sand. Grain boundaries are irregular/ragged due to pressure solution and re-precipitation of silica, and etching of calcite-quartz grain contacts.

Slst: Medium gray, weathers medium brown, very massive, calcite cemented quartz silt. Grades upward into calcareous orthoquartzite as silica cement increases.

Ss: Medium gray, weathers medium brown, very coarse grained, angular quartz sand, slightly calcareous, partially cemented by silica.

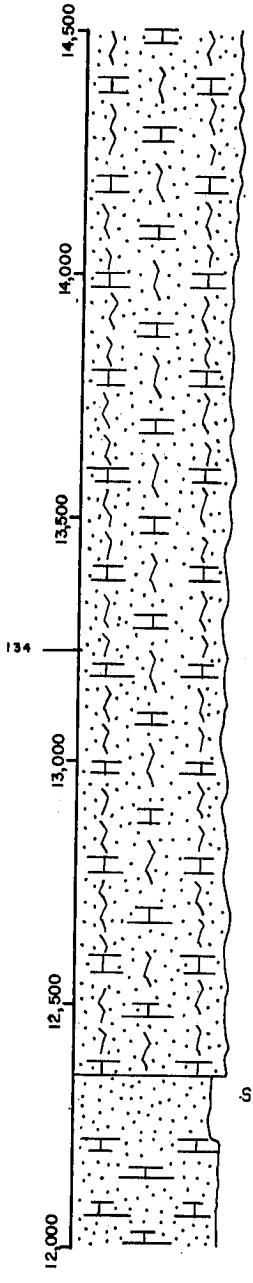
Orthoq: Medium gray, weathers red-brown, silt size quartz grains, calcite matrix, silica cement.

Ss: Yellow brown, weathers gray brown, very fine grained, calcite cemented; trace of porosity.

Slst: Medium gray, weathers medium brown, calcite cemented silt size quartz grains, 5 to 10% clay matrix, 30% calcite.

- covered interval - Tertiary basalt flow -

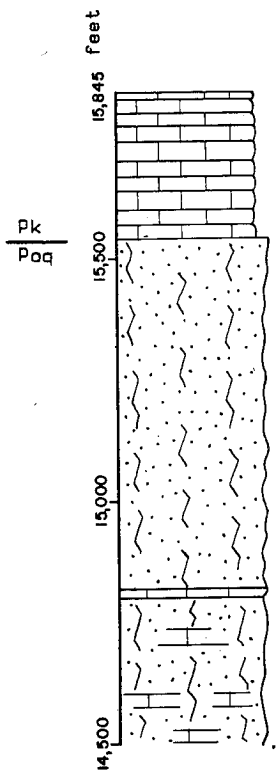
(TEXT-FIG. 2, CONT.)



Orthoq: Light gray to very light brown, weathers light brown, very fine grained quartz sand and silt. Matrix is detrital calcite silt, silica cement. Calcite content ranges from 0 to 7%. Sand grains are quartz (98 to 100%) calcite (0 to 2%), chalcedony and microcline (trace). Weathered portion is non-calcareous, smooth, dense, due to redeposition of silica.

Ss: Dark to light gray, weathers light gray, fine & medium grained quartz sand, calcite & silica cement. Porosity ranges from a trace to 15%. Bedding is generally obscure, with occasional discontinuous, slightly contorted micro-laminae.

(TEXT-FIG. 2, CONT.)



Ls: Mottled brown & dark gray, weathers medium gray; aphanic, with up to 10% vuggy porosity.

Ls: Mottled medium and dark gray, light gray weathering; hard and dense aphanic texture. Calcite veinlets common, up to 2 mm in width.

Orthoq: Light gray, weathers light brown, very fine grained to silt size quartz grains; generally non-calcareous. Highly jointed, breaks with a smooth intra-granular fracture; bedding obscure.

than across grains. These rocks of units 119 and 121 are gradational between friable quartz sandstones and orthoquartzite. Weathered surfaces are generally smoother than fresh rock. This rock is similar to quartz sandstone, except with a larger number of intergrown quartz grains and a decrease in porosity to five percent or less. Original grain shape is increasingly obscured by secondary quartz (Pl. 1, fig. 3).

Calcareous quartz sandstone.—As above, except that a significant amount of calcite is present either as matrix or cement. In unit 98, for example, calcite is present as fine granular silt rather than as a chemical precipitate, and fills interstices between quartz grains. A small amount of silica cement is also present. In the thin sections bedding is commonly visible with layers of fine and very fine grained, well sorted, well rounded, equant, anhedral quartz sand. Grain boundaries are highly etched where quartz is in contact with calcite; quartz intergrowths are rare. Calcite content of 20% is average, and insoluble residues include frosted grains of very fine quartz sand and silt, both as isolated grains and as fragments of porous, friable sandstone and siltstone. Minute veinlets of sparry calcite are also common, as in unit 82 (Pl. 1, fig. 4).

Calcareous quartz siltstone.—As above, except that most quartz grains are of silt size. The quartz grains are well sorted, equant, and angular to sub-angular in shape in unit 87. The rock contains up to five per cent second cycle quartz

and quartzite or sandstone rock fragments. Carbonate content ranges from 10% to 37%, and the residue consists of light gray, vitreous, silty orthoquartzite, siltstone and gray clay (Pl. 1, fig. 5).

Orthoquartzite.—Units 90, 108, 110, and 134 are light gray to light brown, non-calcareous, silica cemented sandstone which breaks with a smooth, subconchoidal fracture. Sand grains, which are not easily seen in the hand sample, are fine to very fine grained quartz (95% to 100%), chert, chalcedony, orthoclase, or microcline. These rocks are typically homogeneous, tenacious, and nonporous. Grains are well sorted, well bedded, and tightly intergrown, and grain boundaries are generally smooth, curved, and deeply embayed. Carbonate content in the samples analyzed was three percent or less (Pl. 2, figs. 2, 3, 4; Pl. 3, fig. 2).

Calcareous orthoquartzite.—As above, with 3% to 30% interstitial calcite matrix. Silica cement still predominates and the rock still displays intragranular fracture in units 3, 5, 105, 131. Minor amounts of detrital microcline, orthoclase, chalcedony, and sandstone rock fragments are present. In many cases silica cementation and quartz intergrowths have developed around detrital calcite grains, giving ragged edges to the quartz. Insoluble residues include clear and frosted grains of quartz sand and silt, and fragments of porous quartz sandstone and siltstone (Pl. 1, fig. 6; Pl. 3, fig. 1).

Calcarenaceous orthoquartzite.—Units 35, 50, and 102 are orthoquartzites which contain detrital calcite sand grains. The cement is silica, and fracture is intragranular. Maximum calcite content observed in this type was 25% in unit 50. The term "calcarenaceous orthoquartzite" (Pettijohn, 1949, p. 305) is mainly a laboratory term, since in the field these rocks often cannot be distinguished from calcareous orthoquartzite, with which they are gradational. In addition to quartz and calcite sand, a certain amount of calcite silt is present. The sand is very fine grained, sub-rounded to well rounded, and the quartz grains are interlocking with crenulated contacts. Insoluble residues consist of light gray to white, hard, dense, vitreous quartzite fragments and very fine quartz and grains (Pl. 2, figs. 5, 6; Pl. 3, fig. 3).

Quartzite breccia.—Units 68, 71, and 81 are composed of a variety of cataclastite which has resulted from local faulting. This rock is a light brown, often friable breccia of very fine grained orthoquartzite fragments, generally less than one centimeter in diameter, scattered in a matrix of coarse, angular, quartz sand and silt. In rare cases, post brecciation recementation by silica has occurred. Calcite content ranges from zero to ten percent in fresh samples, and weathered samples are generally leached of calcite. Insoluble residues consist of angular fragments of quartzite and quartz siltstone, clay, and silt.

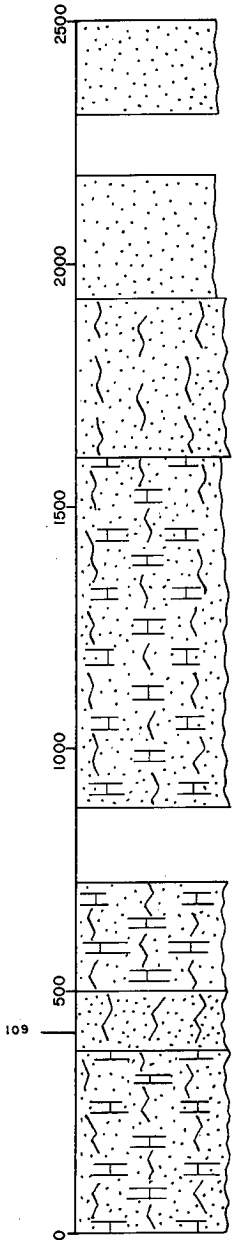
Amount of Exposure

Exposures are fair to good at South Mountain; rocks concealed by soils, landslide debris, and Tertiary lava flows represent six per cent of the section. Minor variations in cementation as well as geomorphic vicissitudes can be responsible for the non-exposure of any interval in a stratigraphic section.

Hobble Creek Canyon Section

Wolfcampian strata of the Oquirrh Formation in Hobble Creek Canyon in Secs. 23, 24, T. 7 S., R. 4 E., and Sec. 18, T. 7 S., R. 5 E., Utah County, Utah, were examined and sampled at regular intervals. Wolfcampian beds

TEXT-FIGURE 3. Columnar section of the Wolfcampian interval, Oquirrh Formation, as exposed in Hobble Creek Canyon (Secs. 23, 24, T. 7 S., R. 4 E., and Sec. 18, T. 7 S., R. 5 E.)



Ss: White to light gray, weathers pale yellow gray; fine to very fine grained pure quartz sandstone, fairly porous, massive.

Orthoq: Light gray, weathers light brownish gray, very fine grained, hard, dense, non-calcareous.

Orthoq: Light gray, very fine grained quartz sand & silt; hard, dense, massive, calcareous, blocky joint pattern.

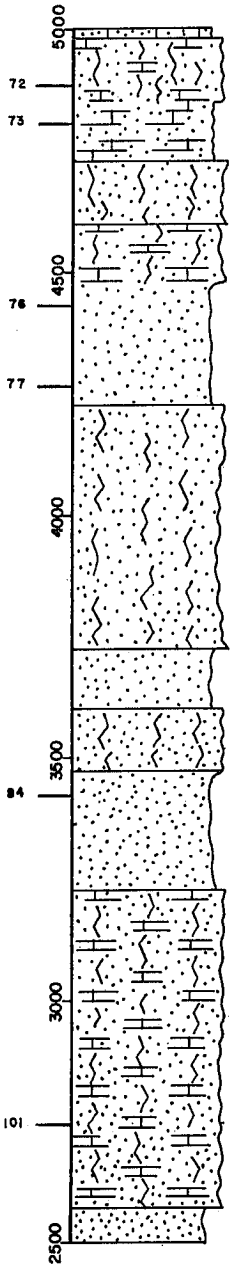
- covered interval -

Orthoq: Light gray, weathers very light gray, very fine grained, dense, calcareous.

Orthoq: Light gray, weathers light brown gray; very fine grained quartz, chalcedony; even bedded, non-calcareous.

Orthoq: Light gray, weathers very light gray; very fine grained, calcareous, non-porous; breaks with smooth intra-granular fracture.

(TEXT-FIG. 3, CONT.)



Ss: Light gray, weathers light brown, very fine grained & silty, very calcareous, bordering on sandy/silty limestone; fossil "worm trails".

Orthoq: White to very light gray, weathers brown, fine grained, non-calcareous, grades upward into calcareous sandy siltstone.

Orthoq: Light gray, weathers very dark brown, very fine grained, hard, dense, calcareous.

Ss: Light gray, weathers light brown, fine to medium grained, non-calcareous; fair to good porosity. Grains are sub-rounded, well sorted, equant, anhedral, partially cemented by silica. Few quartz intergrowths are present.

Orthoq: Light to very light gray, weathers light brown, fine to very fine grained, non-porous, non-calcareous; sharp intra-granular fracture.

Ss: Light gray to white, weathers dark brown, fine grained pure quartz sand, trace of porosity.

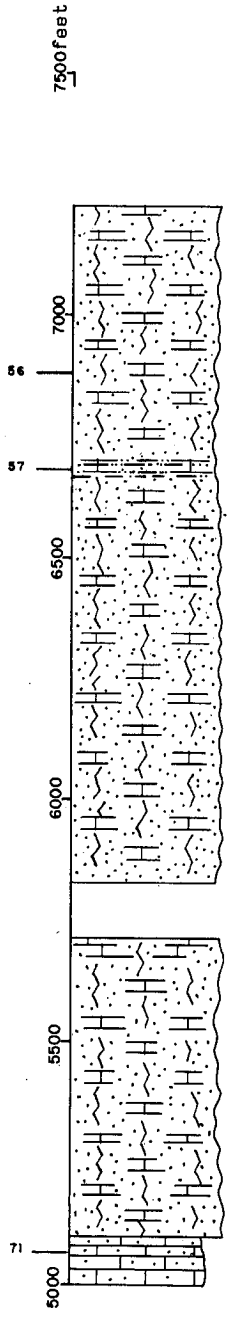
Orthoq: Light gray, weathers light brown, fine grained, hard, dense, non-calcareous.

Ss: Light gray brown, weathers light to dark brown, fine grained, non-calcareous, fairly porous.

Orthoq: Light gray, very fine grained, calcarenaceous, hard, dense, breaks with smooth fracture.

Orthoq: Light gray, weathers light brownish gray, predominantly medium grained (75%), with some fine grained quartz sand (10%), detrital calcite silt (15%), calcite sand (trace); Grains are well rounded, equant, anhedral, with ragged or etched boundaries.

(TEXT-FIG. 3, CONT.)



Orthoq: Light gray, weathers light brown, calcareous, (10 to 23% calcite), very fine grained, non-porous. Grains are quartz, (95 to 97%), calcite (2%), & microcline (trace); matrix is detrital calcite silt (up to 20%), cement is predominantly silica. Grains are poorly sorted, sub-rounded, anhedral, equant, with occasional coarse, rounded & frosted quartz grains distributed at random.

Orthoq: Gray to light gray, brown weathering, fine to very fine grained, hard, dense, calcareous. Develops good porosity in weathered zone.

Ls: Light gray, weathers light brown, contains up to 13% very fine grained sand & silt; residue contains silicified bryozoan & crinoid fragments, gray clay.

here include nearly 7,250 feet of orthoquartzite, calcareous siltstone, and sandy limestone (Baker, 1947, Bissell, 1936, 1962a). These sequences bear striking resemblance to equivalent beds at South Mountain. Best exposures are on the north side of the south fork of Hobble Creek Canyon.

The Hobble Creek Canyon section (Text-fig. 3) was measured by Bissell in 1935 and 1961 and sampled by the writer in 1962. Estimate of thickness is based on information provided by Bissell, on a published section by Baker (1947), and on personal observation in the field. An estimate of relative proportions of rock types present in this section is given in table 1.

Lithology

Orthoquartzite.—Very fine grained, subrounded, interlocking grains of quartz (95% or more), chalcedony, and microcline, cemented by quartz and chalcedony. These rocks of unit 109 are characteristically ridge formers, hard and tenacious, and split with a smooth, subconchoidal fracture. Although this type is apparently non-calcareous in field examination, acid solution reveals up to four percent carbonate present.

Calcareous and calcarenaceous orthoquartzite.—These rocks, in units 56, 72, and 101, consist of very fine grained, silica cemented, quartz sandstone and siltstone, and contain up to 25% of fine calcite silt as a matrix. The rock breaks with a general intragranular fracture, but the broken surface is not as smooth as in the non-calcareous orthoquartzites. In thin section more than half the quartz grains appear intergrown, and grain boundaries are generally ragged and etched. A few random grains of well rounded, coarse quartz and calcite sand are present, and clay content is less than one percent (Pl. 3, figs. 5,6).

Quartz sandstone.—Units 76, 77, and 84 are composed of predominantly fine to medium grained, light gray to light brown, fairly to poorly sorted, friable, quartz sandstone with up to 30% porosity. This type is not common in the section and may represent weathered calcareous orthoquartzite. Carbonate content is two percent or less.

Calcareous siltstone.—Light gray, brown weathering, nonporous siltstone comprises units 57 and 73. Both the weathered and unweathered portions are highly calcareous with up to 34% carbonate. Petrographically, this rock type resembles calcareous orthoquartzite, of which it is a gradational phase. Cement is mainly calcite, with minor amounts of silica and up to three percent clay.

Sandy limestone.—Light gray, sandy to silty, light brown weathering limestone which includes all gradations from sandy, micritic limestone, to bioclastic calcarenite forms unit 71. Occasional traces of authigenic opal, and silicified bryozoan fragments, crinoid columnals, and miscellaneous skeletal material, and siliceous casts of skeletal material are contained.

Amount of Exposure

Exposures of Wolfcamp age strata in Hobble Creek Canyon are generally good, with approximately three per cent of the section covered.

Weber Canyon Section

The Wolfcampian interval of the Weber Formation, on the north-east margin of the Oquirrh Basin, was measured and sampled in Weber Canyon (T. 4 N., R. 3 E.), Morgan County, Utah. This area was part of the Weber

Shelf during much of Pennsylvanian and Permian time, and shows stratigraphic variation from the central to the marginal part of the basin (Text-figs. 1, 5). Thickness of Wolfcampian strata here is 714 feet. The Weber Canyon section is shown graphically in text-figure 4, and relative proportions of rock types present in the section are summarized as table 1.

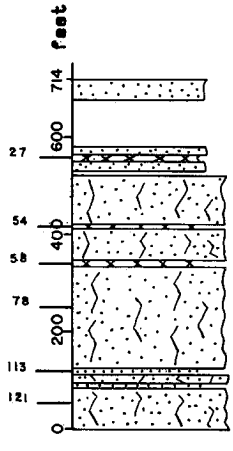
Principal lithologic changes noted in going from basin to shelf areas are absence of calcite in the matrix and cement of clastic rocks, and lack of limestone in the section.

Lithology

Orthoquartzite.—This is the most common rock type in the Weber section, and typically consists of fine to very fine, and silt size, subangular to subrounded, anhedral quartz grains and silica cement in units 58, 78, and 121. Grains have secondary quartz overgrowths and form an interlocking meshwork in which interstices have been filled with precipitated quartz. Porosity varies from a trace to one percent as widely scattered, clay-lined cavities, one quarter millimeter or less in diameter. Grain boundaries are generally smooth and curved to slightly crenulated and embayed, and extinction is normal to moderately undulatory. Traces of detrital orthoclase, microcline, and chalcedony are present. These rocks have a sharp, intragranular fracture and would be difficult or impossible to separate from metaquartzite in a comparison of hand samples (Pl. 3, fig. 4).

Siliceous quartz sandstone.—Unit 113 is composed of rocks similar to the above, but with less complete silica cementation, and a more rough, uneven, intergranular fracture.

Sandstone breccia.—Light gray to light brown breccias made of fragments up to 3 inches long of medium grained sandstone and orthoquartzite, in a matrix of friable, coarse, angular quartz sand compose units 27 and 54. These are the result of local faulting of rocks which, judging from the common association of orthoquartzites with cataclastites, apparently have a low limit of plastic deformation.



Ss: Light gray brown, weathers light gray, fine grained, non-calcareous, pure quartz sand, friable to partially silica cemented; trace of hematite stain.
Ss: Light red gray, weathers gray, medium grained to silt size, slightly quartzitic and limonitic.
Orthoq: Light gray, weathers light gray-brown, very fine to silt size grains, fine laminae, trace of hematite.
Bxa: Light brown, friable, may be fault zone.
Orthoq: As above, with trace of opal cement.
Orthoq: Light brownish gray, weathers gray to dark gray, fine to very fine pure quartz sand, silica cement, with minor feldspar, chalcedony. Trace of porosity, in the form of isolated clay lined cavities.
Ss: Light brown, weathers light gray, very fine quartz sand, trace of silica cement, microcline, chalcedony, clay.
Orthoq: Light gray, weathers light brown, silt size quartz 95%, orthoclase 2%, clay 3%; becomes friable at base.

TEXT-FIGURE 4. Columnar section of the Wolfcampian interval, Weber Formation, as exposed in Weber Canyon (T. 4 N., R. 3 E.), Morgan County, Utah.

Amount of Exposure

Exposures at this locality are good, due to vertical strata and steep canyon walls. Covered intervals comprise 16% of the section and occur mainly in zones of faulting and fault breccia.

TABLE 1

Estimate of relative proportions of rock types in Wolfcampian strata in three sections in central Utah.

	Cumulative Percentage
HOBBLE CREEK CANYON SECTION:	
Orthoquartzite	14
Calcareous orthoquartzite	35
Calcarenaceous orthoquartzite	30
Quartz sandstone	17
Calcareous siltstone and silty limestone	2
Limestone - all other varieties	2
	100
SOUTH MOUNTAIN SECTION:	
Orthoquartzite	10
Calcareous orthoquartzite	24
Calcarenaceous orthoquartzite	20
Quartz sandstone	17
Calcareous siltstone and silty limestone	5
Calcarenite	5
Limestone - all other varieties	14
Breccia	4
Shale	1
	100
WEBER CANYON SECTION:	
Orthoquartzite	80
Quartz sandstone	15
Sandstone breccia	5
	100

Lateral Variations Within the Oquirrh Formation

There are rapid facies changes in the Oquirrh Formation, particularly in the Wolfcampian segment, for individual strata usually die out or merge with adjacent strata within short distances, and seldom persist as much as one-half mile. Abrupt local changes in the character and degree of cementation were noted, particularly near the top of South Mountain. Bedding varies from apparently massive to thin and platy, with quarter-inch laminae, or to other types of stratification, within a few yards laterally. Such changes are believed to be due to subtle differences in cementation, or amount and composition of matrix material. The matrix here is largely a fine carbonate silt of detrital origin.

The overall aspect of the section is generally unchanged from one canyon, or exposure, to the next at South Mountain, but individual lithologic units do not persist. No definite pattern of lateral zonation could be seen in the Oquirrh strata, and directions of facies change appear random.

Attempts at lithologic correlation have not been very successful within the Oquirrh Formation (Wright, 1961, p. 150). Correlation is possible by paleontological studies, and fusulinids have been used successfully by Bissell (1936, 1959b, 1962a, 1962b), Wright (1961), and others to delineate time-rock units.

The lensing character of Oquirrh strata is believed to be a depositional feature, and is not the result of post-diagenetic erosion or strike-slip faulting. Sediment may have been eroded by currents and waves prior to lithification, and redeposited unevenly because of intermittent and irregular subsidence within the basin.

Quartz Types

Quartz grains in the Oquirrh Formation were studied in an attempt to determine a history of the sediment. Common occurrence of detrital chalcedony grains, general deficiency of heavy minerals, presence of quartzite and sandstone rock fragments, scarcity of inclusions in the quartz grains, and lack of euhedral crystal faces on quartz grains all indicate that these quartz sands are at least second cycle sediments derived from pre-existing sedimentary rocks.

Quartz grains in the Oquirrh Formation in the Stansbury Range west of South Mountain, are described by Wright (1961, p. 164) as consisting of two distinct types. These are, (1) angular to sub-angular, silt size to fine grained quartz with normal extinction, and (2) sub-rounded to rounded, medium to coarse grained quartz with undulatory extinction. Both of these types were noted during the present study, in varying amounts, along with several other types. The grains, are mainly silt size to fine grained sand, with rough, embayed, or crenulated borders, moderate undulatory extinction, and whose original grain shape is commonly hidden by secondary quartz.

Criteria suggested by Krynine (1946, p. 40) were applied in the identification of quartz types. The most common type is of sedimentary origin or was derived from sedimentary rocks, identified mainly on the presence of rounded, abraded secondary quartz overgrowths, carbonate inclusions, and dust inclusions which outline the shape of original quartz grains. Plutonic igneous quartz, vein quartz, and pressure type metamorphic quartz are also present. Approximate composition of the quartz sand in the Oquirrh Formation orthoquartzites is as follows:

Sedimentary	50%
Plutonic Igneous	35%
Vein Quartz	10%
Pressure Type Metamorphic	5%

Weathering Characteristics

Surface alteration of calcareous and calcarenaceous orthoquartzites in the temperate, semi-arid climate of the eastern Great Basin commonly produces a concentric series of zones or rinds which are readily seen on broken rock surfaces. The outer zone is generally a brown or dark brown, porous, friable quartz sandstone from which calcite has been leached, and clay and iron oxide content increased to about five percent. In some cases, particularly those rocks with a lower original calcite content such as unit 134 at South Mountain, the outer surface of this zone will be casehardened, with a thin veneer of smooth, dense silica. Contact of the weathered and unweathered zones is fairly sharp and represents the maximum depth of effective water penetration. Weathered zones range from one-eighth inch to several inches thick, but are usually less than two inches deep. Nature of the weathered surface is a function of lithology, climate, drainage, and length of time that the rock has been exposed.

Zonation is strongest in samples from Hobble Creek Canyon, which is likely due to increased precipitation and heavier vegetation at this locality, but which may also reflect subtle lithologic differences.

Porosity of weathered zones may be as much as twenty percent or more, sufficient to permit migration of fluids, were this zone encountered in the subsurface.

Cementation

Cement most commonly found in sandstone is silica and carbonate. Sufficient cementation of pure quartz sandstones by silica under normal sedimentary conditions produces an orthoquartzite. Cementation occurs by addition of silica to the environment, by pressure solution of the quartz grains, or by a combination of these processes.

Addition of silica to a sand under conditions of low pressure gives rise to euhedral overgrowths on the quartz grains, usually in optical continuity with the original grain. Euhedral faces are likely to develop if the sand is porous and loosely packed, and if the grains do not interpenetrate each other. Silica may originate as a product of mineral alteration, such as alteration of montmorillonite to illite in interbedded clays (Towe, 1962, p. 26), or by replacement of quartz or chert by carbonate, or from connate water or ground water.

Pressure solution phenomena develop because increased pressure on a solid reduces the melting point of that solid for any given set of chemical conditions. Quartz dissolves at the points of highest pressure, especially in zones of high pH, and is precipitated at points of lower pressure and low pH. Presence of interstitial clays and water is important. The clay contributes potassium ions, which are replaced by calcium and magnesium ions through base exchange, and K_2CO_3 forms, which raises the pH in clay-rich zones. The water aids in silica solution, and acts as a vehicle for migration of the dissolved silica (Thomson, 1959, p. 106). Compaction thus proceeds, and grains become tightly packed and usually interpenetrating.

Cementation of the orthoquartzites in the Oquirrh Formation at South Mountain and at Hobble Creek Canyon is apparently the result of combined pressure solution and addition of new silica. The majority of orthoquartzite thin sections examined shows quartz grains welded together both by interpenetration and by deposition of secondary silica in pore spaces as rims or overgrowth on original quartz grains. Grain contacts are, in the absence of carbonate, sinuous, curved, and sutured. In calcareous and calcarenaceous orthoquartzites the effect of calcite has been development of rough, etched grain borders. However, intergrown quartz grains still predominate.

The Weber Formation thin sections also show both pressure solution and secondary overgrowths, although euhedral overgrowths are rare. Grain boundaries are embayed and crenulated to the extent that original grain shapes are obscured.

Implications are that there was a plethora of silica in the Oquirrh Basin during deposition of the Oquirrh Formation or shortly thereafter, and that strong tectonic forces were active in the area. Furthermore, the abundance of silica makes it unlikely that zones of good porosity would be encountered in Wolfcampian strata of the formation in the subsurface.

TECTONIC SETTING

Excellent summaries of the tectonic history of central Utah during late Paleozoic time are given in reports by Bissell (1952, 1962a) and Wright (1961). It is felt that a brief resumé of the ideas of these and other authors

is appropriate to a discussion of orthoquartzite of the Oquirrh Formation so that these rocks may be considered in their proper geological context.

Regional Sketch

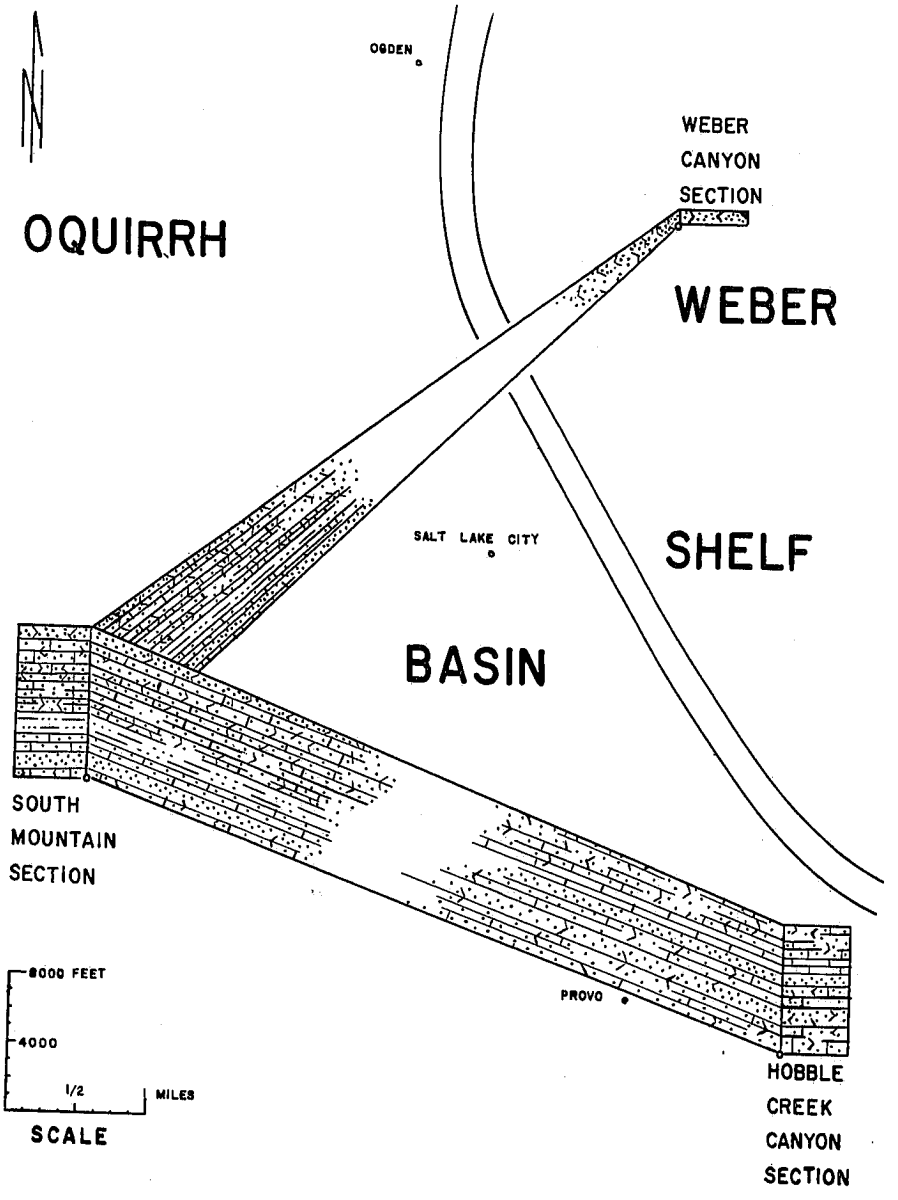
The area occupied by the Oquirrh Basin was part of the Cordilleran Geosyncline during Early Paleozoic time. From the Devonian until the end of the Paleozoic, the older orthogeosyncline was divided by a geanticline which arose in western and central Nevada and which effectively separated the western eugeosyncline from the eastern miogeosyncline (Nolan, 1943; Bissell, 1952, p. 625). The approximate western limit of the late Paleozoic miogeosyncline is termed the Manhattan Line, and bisects the state of Nevada in a nearly north-south direction along the Antler-Sonoma orogenic belt (Bissell, 1960, p. 1425). The eastern limit, a line of flexure called the Wasatch Line (Kay, 1951, p. 14), follows approximately the eastern edge of the Great Basin geomorphic province. The Wasatch Line separated the miogeosyncline from the stable shelf and cratonic areas to the east. This hinge line is a narrow zone of rapid change in sedimentary thickness and lithology, and it is across this line that the Oquirrh and Weber formations interfinger (Text-fig. 5). It is immediately west of the Wasatch Line, in the eastern part of the miogeosyncline, that the thickest known section of Pennsylvanian and Permian rocks found anywhere in the United States, with the possible exception of the Ouachita Mountain region of Oklahoma and Arkansas, accumulated (Nolan, 1943; Bissell, 1962b). End of the miogeosyncline came toward the close of the Permian period. No Late Permian rocks are known in the area, and Triassic strata were deposited unconformably on the Permian rocks.

Depositional Environment

The overall depositional pattern in the Oquirrh Basin was one of clastic sedimentation, including both quartz and calcite sand and silt, with intermittent shorter periods of limestone deposition. Lithologic variability, abrupt changes in thickness of individual units, and abundance of clastic materials indicate that Pennsylvanian and Early Permian was a time of general instability. Subsidence was continuous but uneven, with considerable local adjustment. It is possible that littoral and lagoonal sediments were deposited at various places within the basin, but, if so, much of the sequence was destroyed by erosion. That erosion occurred at various times is suggested by numerous small unconformities and diastemic breaks observed at South Mountain and in Hobble Creek Canyon.

Environments ranged from infraneritic to epineritic and epineritic biostromal, with water depth variable but probably never more than a few hundred feet (Bissell, 1952, p. 585). Sediments are in general fairly well sorted and rounded, which, coupled with a deficiency in clay size material, indicates long periods of washing and, indirectly, transportation over long distances. Current ripple marks and small scale cross bedding are commonly apparent on weathered surfaces, but silica cementation tends to obscure these and other primary structures. Areas of thickest accumulation of sediment varied from epoch to epoch, as shown on isopach maps published by Bissell (1962a).

Precipitation of silica cement in an environment where carbonate sediments are forming requires rather precise geochemical conditions. According to Krauskopf (1959, p. 10) silica does not precipitate above a pH of 8.8. Calcite



TEXT-FIGURE 5.—Fence diagram showing relationships of the Wolfcampian strata of the Oquirrh and Weber Formations in a portion of Central Utah.

does not precipitate appreciably below a pH of 8.0 (Krumbein and Garrels, 1952, p. 26). The oxidation potential (E_h) may be either positive or negative, and is apparently not a controlling factor.

Paleogeography

Borderland areas adjacent to the Oquirrh Basin during the Pennsylvanian and Early Permian include the Weber Shelf to the northeast, the Northeast Nevada Highland to the northwest, the Western Utah Highland to the west and southwest, the Callville-Hermosa Platform to the south, and the Emery Uplift to the southeast. These positive areas were breached at various places by inlets or accessways which permitted contact with open ocean waters, and through which considerable amounts of sediment may have been transported to the basin.

During Medial and Late Wolfcampian time there was a pronounced decrease in size of the Oquirrh Basin, probably due to an interruption of the relatively rapid rate of subsidence experienced earlier. Eolian sediments of the Diamond Creek and upper Weber Formation covered the Weber Shelf, and the littoral and epineritic Kirkman Limestone was deposited over the Oquirrh sediments (Bissell, 1962a, p. 46).

Paleontologic Evidence

Limestone units of the Oquirrh Formation contain a varied fauna, principally fusulinids, crinoids, bryozoans, brachiopods, corals, and various forms of algae. Of these, the most widely distributed, both arealy and stratigraphically are the fusulinids.

Fusulinids are predominantly benthonic calcareous foraminifera which apparently were tolerant of a wide range of environmental conditions. Rock types in which they generally are found include a wide variety of limestones, sandy limestones, and calcareous shale and siltstone (Slade, 1961, p. 90; Weller, 1957, p. 353). Normally fusulinids thrived in fairly quiet marine waters at depths considered to range from one to thirty fathoms (Dunbar, 1957, p. 753; Tasch, 1957, p. 396). Variation in fusulinid lithotopes, and their common occurrence in layers which are barren of other organisms indicates that they were tolerant of greater ecological extremes.

Occasional local abundance of corals, crinoids, algae, brachiopods, and bryozoans indicates that at times the water was shallow enough to permit penetration of sunlight, sufficiently agitated to provide sufficient oxygen and nutrients, and also clear enough to permit these forms to flourish. A picture of shifting environments, oscillating between littoral, epineritic, and infraneritic conditions, with generally moderate to strong bottom currents and abundant clastic sediment supply, with continuous subsidence is compatible with paleontological evidence.

Rate of Sedimentation

The unusual thickness of the Oquirrh Formation has prompted the writer to investigate the rate of sedimentation for the unit, and to compare this with calculated rates of other Late Paleozoic accumulations. A thickness of 16,000 feet of Pennsylvanian age sediments was used in the calculations, which includes 15,000 feet of Oquirrh Formation and 1,000 feet of Pennsylvanian age Manning Canyon Formation. The Pennsylvanian period, according to Kulp (1959, p. 1634) lasted 55 million years. The calculated average rate of Oquirrh

sedimentation is 290 feet per million years, or 3435 years per foot of sedimentary rock (Table 2).

This rate is somewhat greater than the maximum miogeosynclinal rate given by Kay (1951), but less than the maximum rate cited for intracratonal geosynclines. Apparently the Oquirrh Basin was more active than most miogeosynclinal basins, and more similar to intracratonal basins in its tectonic behavior.

TABLE 2

Calculated rates of deposition of sedimentary rocks in geosynclines.

	Feet per million years:	Years per foot:	Reference:
Maximum for Late Paleozoic	692	1445	Pettijohn, 1957, p. 688
Maximum for miogeosynclines	202	4950	Kay, 1951, p. 96
Average maximum for North American intracratonic geosynclines	317	3155	Kay, 1951, p. 95
Oquirrh Basin	290	3435	This report

COMPARISON WITH QUARTZITES FROM OTHER FORMATIONS

As far as could be determined by the writer, the variety of calcarenaceous orthoquartzite predominating in the Oquirrh Formation has not been found elsewhere. A comprehensive review of the standard texts on sedimentary petrology (Dunbar and Rodgers, 1958; Pettijohn, 1949 and 1957; Krumbein and Sloss, 1951; Williams, Turner, and Gilbert, 1954; Carozzi, 1960; Barth, 1960) and of the periodical literature failed to produce any reference to other rocks of similar lithology.

To provide a basis for comparison of the orthoquartzites in the Oquirrh Formation, and also to see whether a random sampling of other quartzites would turn up rocks of similar lithology, quartzites from a number of other formations were investigated. Approximately 35 formations from different areas and several systems were considered, and from these about two dozen thin sections were prepared. Study of these rocks failed to reveal any other examples of calcarenaceous orthoquartzite. Similarities in texture, nature of the quartz grains, and in the type of cement were noted, but the combination of fine and very fine quartz sand, carbonate silt, and silica cement was not found.

Observations on Quartzites in General

As a result of the study of the thin sections from the Oquirrh, Weber, and other formations, some additional observations were made which seem to indicate characteristic aspects of quartzite lithology. Certain petrographic properties observed in most or all of the quartzites examined are listed below.

Petrographic Characteristics

Nature of the Cement.—Cementation in orthoquartzite is mainly a combination of pressure solution of detrital quartz grains and addition of new silica, but occasionally examples may be found where these processes have occurred separately.

High Quartz Content.—The detrital fraction of more than 95% of the thin sections analyzed contained at least 95% quartz, including detrital chert grains and quartzose rock fragments. More than 91% contained 99% quartz.

Light Color.—More than 75% of the samples examined were, megascopically, light shades of gray, brown, pink, etc., and none of the thin sections were measurably colored.

Lack of Porosity.—There is a complete lack of effective porosity in orthoquartzites. More than 90% of the samples studied had less than 1% isolated pore spaces, and none had as much as 5%.

Idiomorphism.—Detrital quartz in the orthoquartzites examined consisted of essentially all anhedral grains. Occasionally grains of subhedral vein quartz are found, and in some cases crystal faces may develop on secondary quartz which formed in veins or cavities in an orthoquartzite after diagenesis.

Dissimilarities

Some properties of the examined orthoquartzites are consistently variable, such as grain size, sorting, roundness of grains, nature of grain boundaries, inter-grain relationships, and inclusions present in the quartz grains.

Orthoquartzite versus Metaquartzite

Differentiation of orthoquartzite from metaquartzite has traditionally depended upon a study of field relationships of the rocks involved, or the identification of characteristic metamorphic minerals which might be present in any given sample. Although no new infallible rules for separating orthoquartzite from metaquartzite can be established from this study, certain indicative criteria are suggested. These include the following:

Orthoquartzite Criteria

Foliation.—Non-foliated; bedding and cross bedding may or may not be present.

Grain shape.—Detrital grain outlines may be visible enclosed in secondary silica; may have any degree of rounding.

Grain packing.—Grains may be tightly packed and intergrown, or, loosely packed with a fair amount of minus cement porosity.

Extinction.—Most quartz grains show moderate strain shadows, some have normal extinction.

Deformation.—Fractures commonly seen in thin section, cutting across grains and cement.

Faunal evidence.—May contain unaltered plant or animal fossils.

Metaquartzite Criteria

Foliation.—Will show a parallel or sub-parallel orientation of new minerals, such as micas, provided the materials are available for development of these minerals.

Grain shape.—Original grain shape obscured by recrystallization; absence of dust rims.

Grain packing.—Grains are tightly packed, intergrown and interlocking, with crenulated or sutured grain contacts.

Extinction.—Highly undulatory with strong strain shadows.

Deformation.—May be evidence of shearing in crushed, strung out, and recrystallized grains.

Faunal evidence.—Preservation of fossils unlikely.

Since processes of metamorphism are gradational with those of diagenesis, no sharp line can be drawn between orthoquartzite and metaquartzite. Some of the criteria listed above under metaquartzite may develop to some degree during diagenesis and be found in orthoquartzite.

SUMMARY STATEMENT

Calcarenaceous orthoquartzite in the Oquirrh Formation is a lithology unique, or at least uncommon in American stratigraphy. Reasons for development of this anomalous lithology are obscure, but certain clues may be gained from a study of the sediments, their sources, and their environments of deposition. Calcareous sediment in the calcarenaceous orthoquartzite is probably derived from within the basin. The quartz sand is probably a mixture of materials derived from the various highlands adjacent to the Oquirrh Basin and contributed from outside the basin. Much of this is second cycle sediment. A possible source of the chemically precipitated silica is the volcanic area in the Cordilleran eugeosyncline to the west. Conditions which prevailed within the basin permitted chemical precipitation of both calcite and silica. These conditions persisted throughout most of Pennsylvanian and Wolfcampian time, while sufficient subsidence was taking place so that nearly five miles of sediment accumulated (Bissell, 1962b, p. 1106).

CONCLUSIONS

1. The Oquirrh Formation constitutes an unusual suite of sedimentary rocks which reflect conditions of tectonics and sediment supply which are perhaps unique in geologic history. The Oquirrh Formation is unique in its great thickness, in the lack of shale or claystone, and in the abundance of calcarenaceous orthoquartzite.

3. Shallow water marine conditions prevailed in the Oquirrh Basin during Pennsylvanian and Early Permian times in conjunction with tectonic conditions of irregular instability and deep subsidence.

3. Sediment of the Oquirrh Formation was derived from various adjacent land masses, from local positive areas within the Oquirrh Basin, and perhaps also contributed from beyond the basin through peripheral accessways. This material was subjected to effective sorting and cleaning by wave and current action.

4. Orthoquartzite and calcarenaceous orthoquartzite of the Oquirrh Formation are rock types which do not fit neatly into the present system of sed-

imentary rock nomenclature; therefore caution should be exercised when describing these rocks or when studying published descriptions of Oquirrh strata.

5. Classification of lithoclastic sedimentary rocks is in need of revision and standardization, and those who are active in the revision should be aware of rock types such as are herein described.

6. The term orthoquartzite is a useful one which describes an important group of sedimentary rocks. It should be applied discreetly, however, with due regard to its original meaning and traditional usage.

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Manuscript received April 30, 1963

EXPLANATION OF PLATE 1

PHOTOMICROGRAPHS OF TYPICAL OQUIRRH FORMATION ROCKS FROM SOUTH MOUNTAIN.

FIG. 1. Calcarenite. Consists of skeletal material and detrital carbonate grains in micrite. Unit 1, plain light, 24x.

FIG. 2. Quartz sandstone. Predominantly very fine quartz sand with a small amount of silica cement. A microcline grain is in lower center. Unit 91, crossed nicols, 24x.

FIG. 3. Siliceous quartz sandstone. The original grain shape is obscured by contiguous quartz cement. Unit 121, crossed nicols, 24x.

FIG. 4. Calcareous quartz sandstone. Matrix material is calcite silt; both calcite and quartz cement are present. A calcite vein occurs near center. Unit 82, crossed nicols, 24x.

FIG. 5. Calcareous quartz siltstone. Clastic material is mainly quartz silt, with some calcite, in a mixture of micrite, clay, and authigenic silica. Unit 87, crossed nicols, 24x.

FIG. 6. Calcareous orthoquartzite. Edges of some quartz grains have been etched by calcite, giving them a ragged appearance. Unit 131, crossed nicols, 24x.

EXPLANATION OF PLATE 2

PHOTOMICROGRAPHS OF TYPICAL OQUIRRH FORMATION ORTHOQUARTZITES FROM SOUTH MOUNTAIN

FIGS. 1, 2, 3. Orthoquartzite. 1, Shows silica cementation and isolated, clay filled pore spaces. Unit 108, plain light, 24x; 2, same as 1, crossed nicols, Note optical continuity of quartz cement with original quartz grains. 24x; 3, an enlargement of 2, showing detail of grain-cement relationships. Original grain shapes can sometimes be seen as a line of dust or clay inclusions within the secondary silica. Crossed nicols, 24x.

FIG. 4. Orthoquartzite. Cement is mainly quartz, with chalcedony. Cementation has obscured original grain shape and produced the interlocking texture typical of quartzites in general. Unit 110, crossed nicols, 24x.

FIGS. 5, 6. Calcarenaceous orthoquartzite; 5. A mixture of quartz sand, calcite sand and silt, bonded by silica cement. Unit 50, crossed nicols, 24x; 6. Same as 5, plain light. Medium-gray material is calcite sand. 24x.

EXPLANATION OF PLATE 3

PHOTOMICROGRAPHS OF ORTHOQUARTZITES FROM THE OQUIRRH FORMATION AT SOUTH MOUNTAIN AND HOBBLE CREEK CANYON, AND FROM THE WEBER FORMATION IN WEBER CANYON.

FIG. 1. Calcareous orthoquartzite from South Mountain. Note optical continuity of some intergrown quartz grains and abundance of carbonate silt. Acid solution indicates a carbonate content of 29%. Unit 3, crossed nicols. 24x.

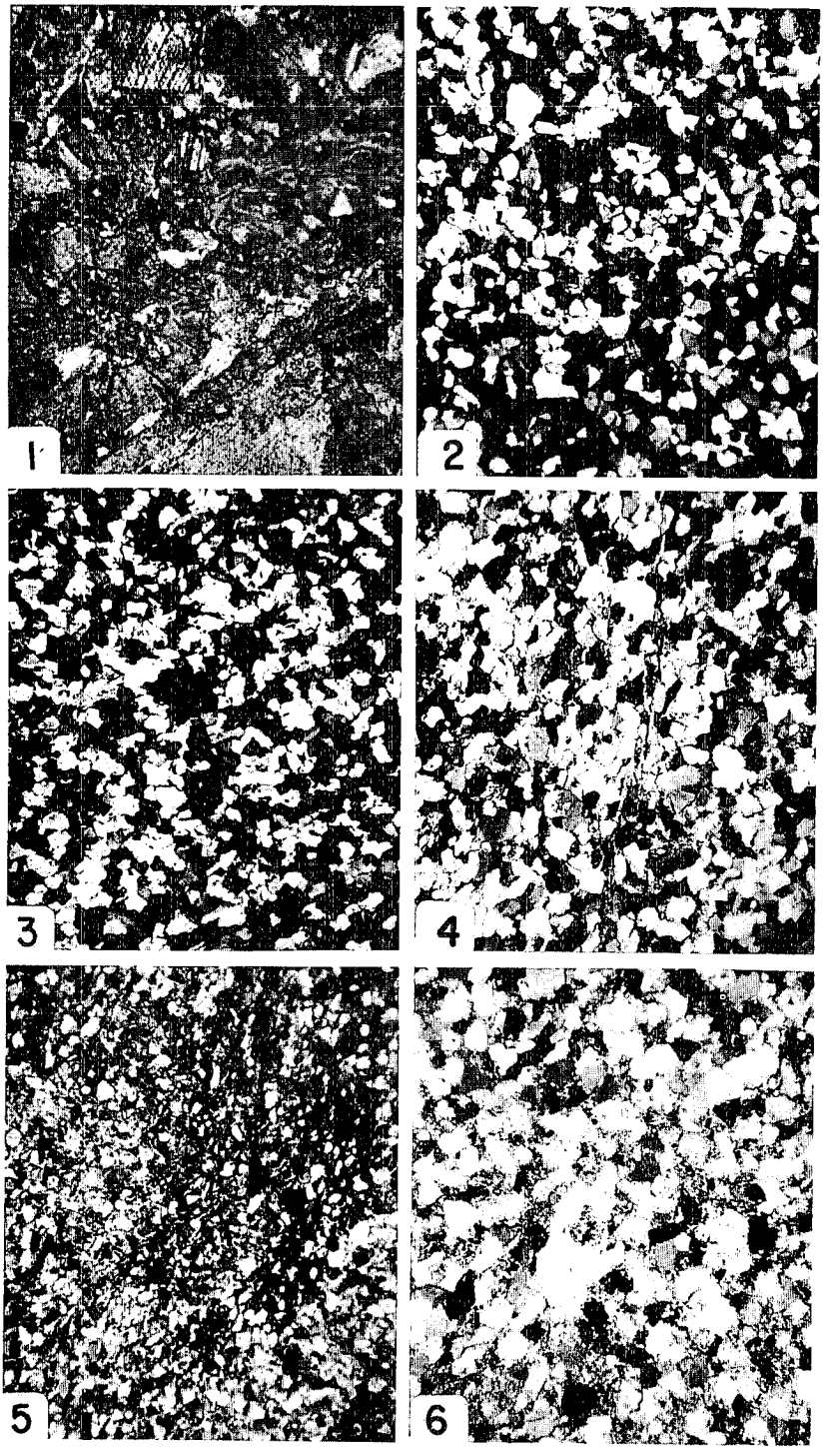
FIG. 2. Orthoquartzite from South Mountain. Secondary quartz has overgrown large grain to the right of center, delineated by enclosed dust rim. Unit 134, crossed nicols, 24x.

FIG. 3. Calcarenaceous orthoquartzite from South Mountain. Calcite sand grains appear as medium-gray, granular grains in upper right and lower left, with silica cement. Unit 35, crossed nicols, 24x.

FIG. 4. Orthoquartzite, Weber Canyon section, unit 78. Abundance of silica cement, high degree of sorting, and complete absence of carbonate are typical. Crossed nicols, 24x.

FIGS. 5, 6. Calcarenaceous orthoquartzite from Hobble Creek Canyon section, unit 101. Large, well rounded grains in upper center are carbonate, plain light, 32x; 6. Same as 5, crossed nicols. Both sand and silt size carbonate material are present. 32x.

PLATE 1 — RICHARD B. WELLS



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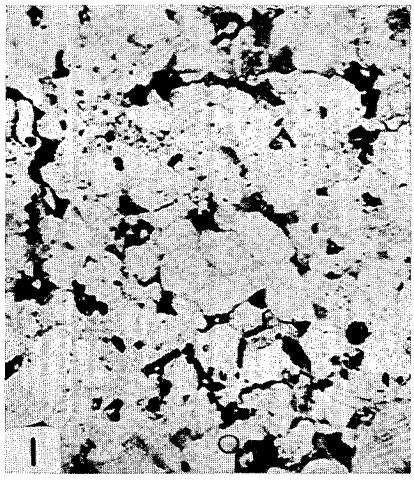
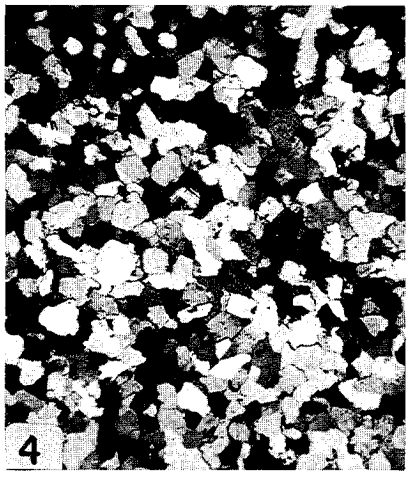
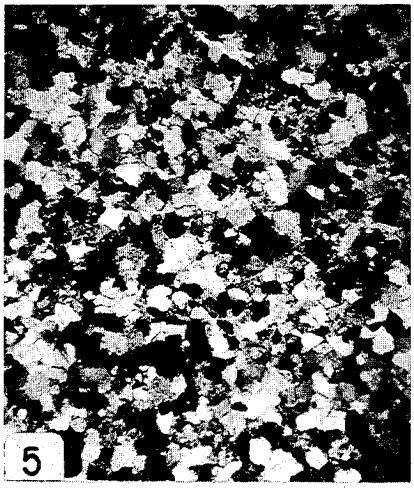






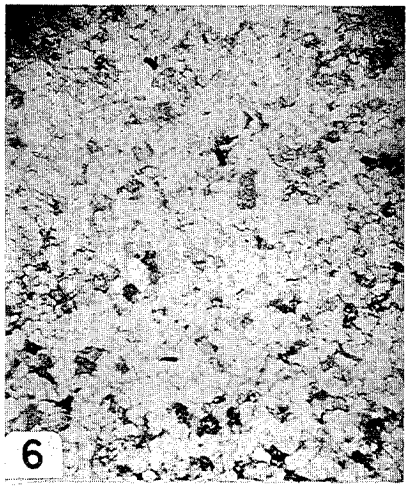


PLATE 3 — RICHARD B. WELLS

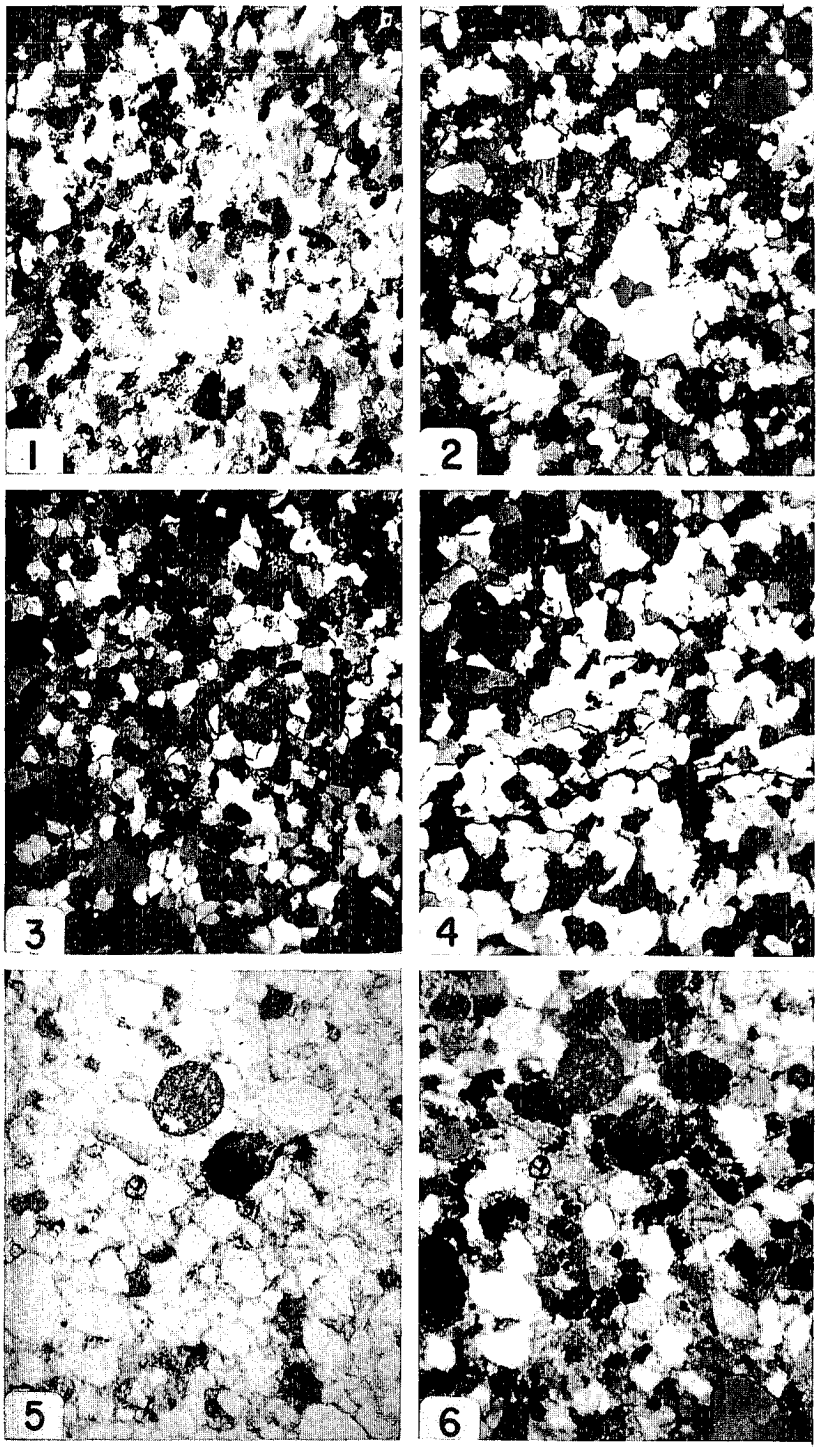
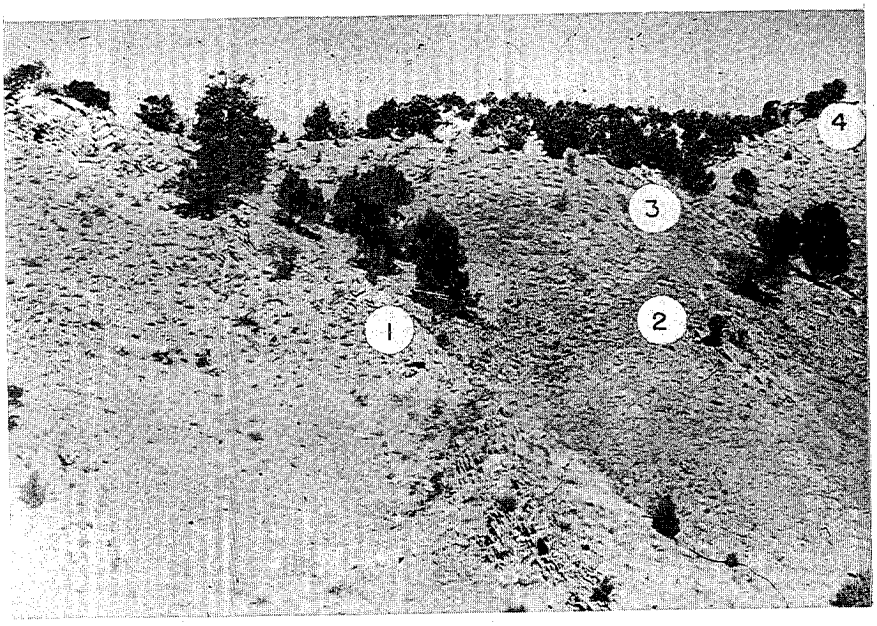


PLATE 1 — DONALD PRINCE



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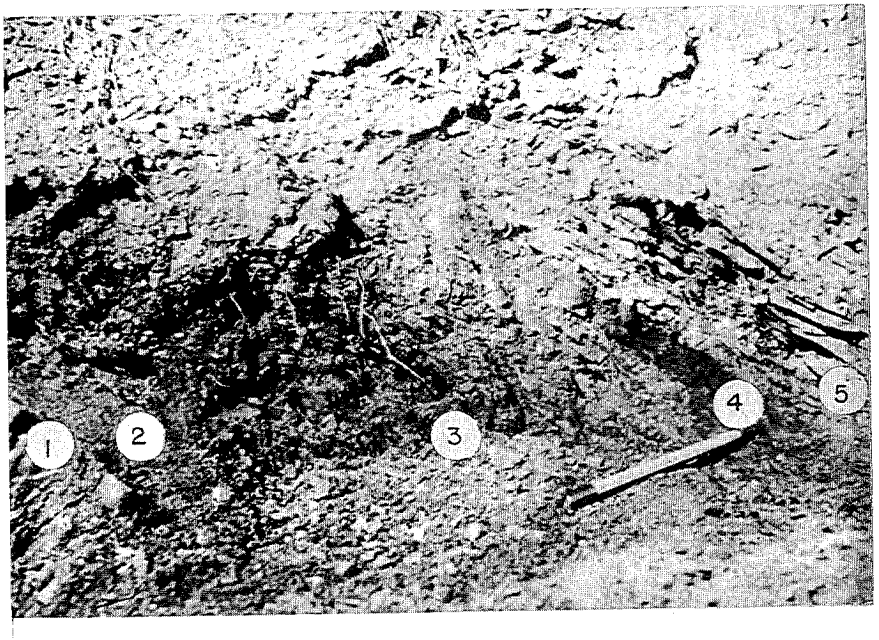

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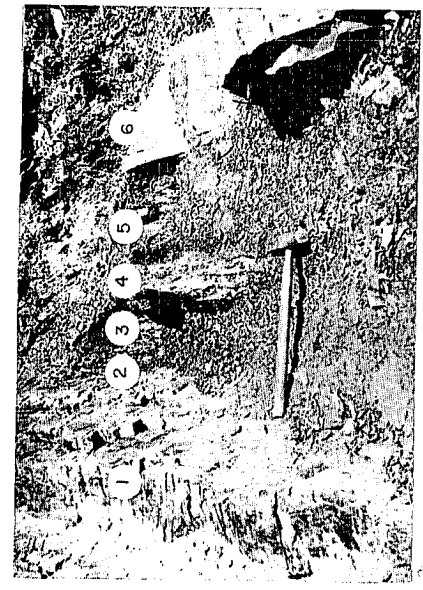

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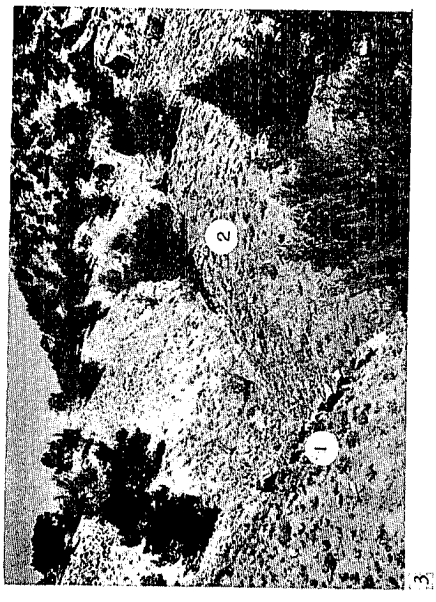

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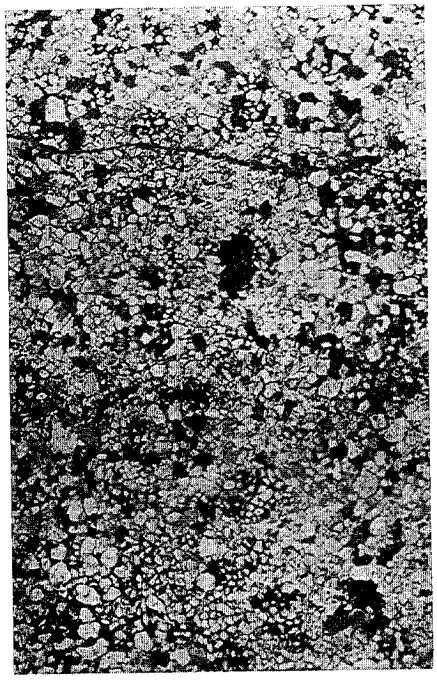

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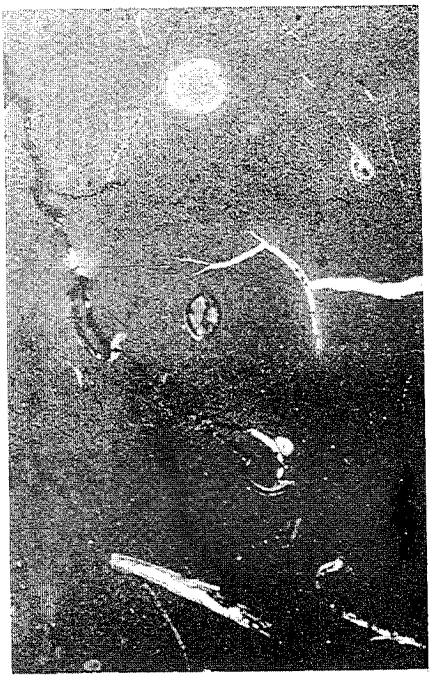

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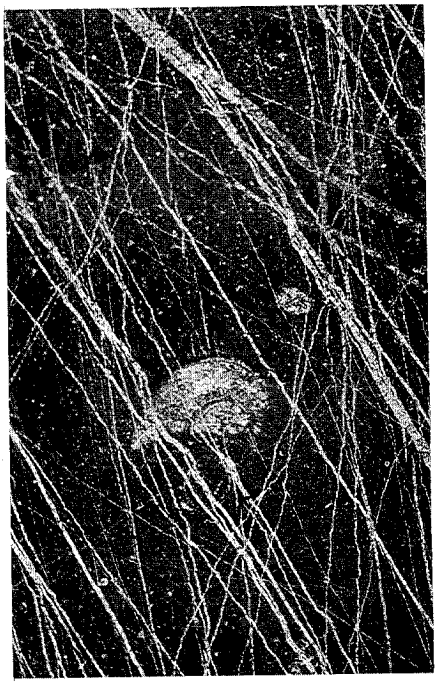

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EXPLANATION OF PLATE 1

MANNING CANYON SHALE OUTCROPS IN SOLDIER CANYON

FIG. 1. Spur where detailed section was measured, seen from the east: 1, "medial limestone"; 2, quartzite of lower cyclothem unit 66; 3, quartzite of upper cyclothem, unit 130; 4, limestone of upper partial cycle, unit 189.

FIG. 2. Trenched exposures of lower part of lower cyclothem: 1, quartzite; 2, sandy shale; 3, underclay; 4, coal; 5, roof shale.

EXPLANATION OF PLATE 2

MANNING CANYON SHALE OUTCROPS IN SOLDIER CANYON

FIG. 1. Unchanneled basal contact of quartzite of upper cyclothem, unit 130, on measured spur. Hammer is fifteen inches long.

FIG. 2. Trenched exposures of lower part of the upper cyclothem, detailed section: 1, basal quartzite; 2, sandy shale; 3, underclay; 4, coal; 5, roof shale; 6, limestone. Hammer is fifteen inches long.

FIG. 3. Characteristic outcrops of cyclothems on the spur west of detailed section (locality 2, Text-fig. 1): 1, lower quartzite; 2, middle quartzite.

FIG. 4. Part of the Jenny section as exposed in a road cut above the prospect (locality 1, Text-fig. 1): 1, lower coal; 2, upper coal.

EXPLANATION OF PLATE 3

PHOTOMICROGRAPHS.
All x 10, plain light

FIG. 1. Quartzite of lower cyclothem, unit 66.

FIG. 2. Nodular roof shale of lower cyclothem, unit 70, with ostracodes and pelecypods.

FIG. 3. Limestone of upper cyclothem, unit 137, gastropods and ostracodes.

FIG. 4. Marine limestone of limestone-shale sequence, top of "medial limestone", unit 22, pelecypods and crinoids.

Mississippian coal cyclothems in the Manning Canyon Shale of central Utah*

DONALD PRINCE

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ABSTRACT.—Late Mississippian coal cyclothems occur within the Manning Canyon Shale in Soldier Canyon, five miles southeast of Stockton, Tooele County, Utah. The cyclothems are Chesteran and Springeran age and exhibit typical lithology—quartzites, underclays, coal, roof shales, and limestones.

A stratigraphic section of the middle third of the formation was measured in detail by shallow trenching, and totaled 285 feet. Within this interval exist a lower marine limestone-shale sequence, a lower coal cyclothem, an upper coal cyclothem and an upper partial cycle. The cyclothems are highly asymmetrical with marine strata dominating. Seas, during deposition of the cyclothems, were generally transgressive with alternating short regressive stages. The two cyclothems exhibit characters which compare favorably with mid-continent cyclothems and probably reflect similar environments.

The lower cyclothem is 63 feet thick, 60 feet of which is marine, and is a simplified sequence consisting of a resistant basal quartzite, thin sandy shale and underclay, coal and roof shale. The coal is lenticular, highly weathered lignite, varying from one to two inches thick.

The upper cyclothem is more complete but thinner, 26 feet thick, of which 15 feet is marine; it contains seven of the possible ten members found in the standard idealized mid-continent cyclothem. The same five units of the lower cyclothem are present with an overlying black, fossiliferous limestone and upper shale sequence. The coal is lenticular, brown, banded lignite, varying up to five inches. Gypsum is associated with the coal and the overlying 13 inches of roof shale.

The upper partial cycle consists of a four-foot resistant quartzite and overlying black shales. A thin sandy shale is present immediately above the quartzite, but clay and coal are not present. Abrupt subsidence probably eliminated the environments necessary for the development of underclay and coal.

Cyclothems reflect instability with prolonged marine transgressive and alternating brief regressive nonmarine cycles.

CONTENTS

TEXT

ILLUSTRATIONS

*A thesis submitted to the Faculty of the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science.

CONTENTS (CONT.)

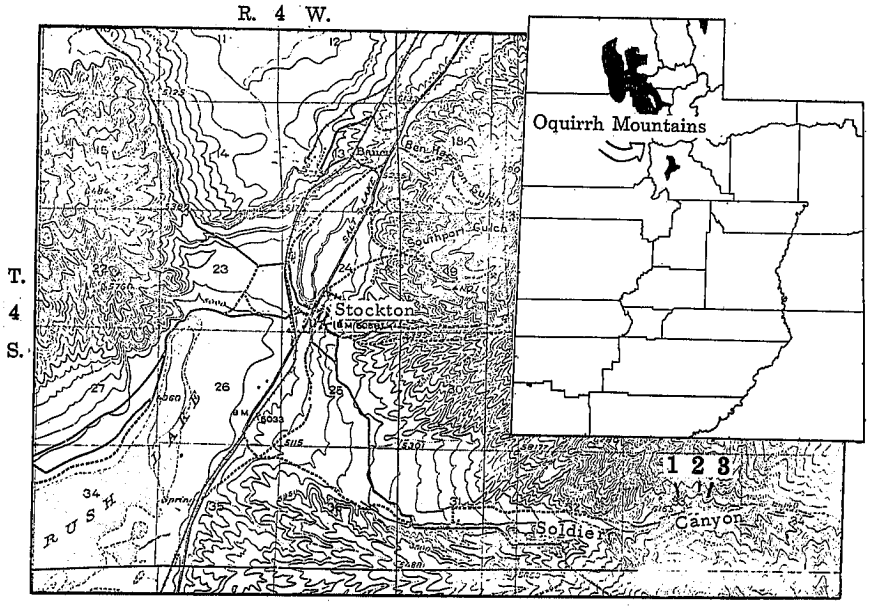
INTRODUCTION

The Manning Canyon Shale in Soldier Canyon contains a wide variety of sediments, part of which are deposited in typical mid-continent-type coal cyclothems. Cyclothem, as used here, denotes cyclical sedimentation typical of coal measures containing sandstone or quartzite, underclay, coal, roof shale, and limestone. No previous coal cyclothems have been reported in central Utah. Two coal beds are present and with their associated sediments compose two cyclothems. A partial third cycle is also present in Soldier Canyon. The presence of these cycles and their similarities with mid-continent types suggests certain paleoenvironments.

The purpose is to describe the cyclothems in detail, discussing their physical character, thickness, fossils, and to reconstruct the sedimentary environments. Since the formation is well exposed at only one location, long distance correlation is difficult if not impossible. The study, therefore, was mainly limited to one detailed section with generalized correlations in adjacent areas.

Location and Setting

Soldier Canyon is in the west central Oquirrh Mountains of central Utah, approximately five miles southeast of Stockton, Tooele County, Utah (Text-fig. 1) and is readily accessible by graded road. Soldier Canyon has been cut perpendicular to the axis of the north plunging nose of the Ophir anticline; Soldier Creek



TEXT-FIGURE 1.—Index and locality map: 1, Jenny section; 2, middle spur; 3, detailed measured section.

drains westward into Rush Valley. The canyon is underlain by Manning Canyon Shale except near the mouth where the formation is exposed on the north wall. The measured section is on the north side of the canyon, three spurs east of the Jenny (Marjorie) prospect and mine dump, one-half mile above the canyon mouth, in the SE¼, NE¼, Sec. 33, T. 4S., R.4W., Salt Lake Base and Meridian (Text-fig. 1). An additional partial section was measured due north of the Jenny mine dump in a road cut. (Pl. 1, fig.1; Pl. 2, fig. 4).

Previous Work

The Manning Canyon Shale crops out widely throughout central Utah. Gilluly (1932, p.31) named the formation from exposures in Manning Canyon, southeast of Soldier Canyon. He stated, "The section measured in Soldier Canyon is believed to represent the formation better than any of the others".

Sadlick (1955) measured a section in Soldier Canyon and stated that the Mississippian-Pennsylvanian boundary could not be precisely located.

Moyle (1958) measured a complete section, 1559 feet, in Soldier Canyon, in addition to studying nine other Manning Canyon sections in central Utah. His work is the most extensive and complete to date. The present study is on the same Soldier Canyon section, investigating in greater detail 285 feet of the middle part of the formation.

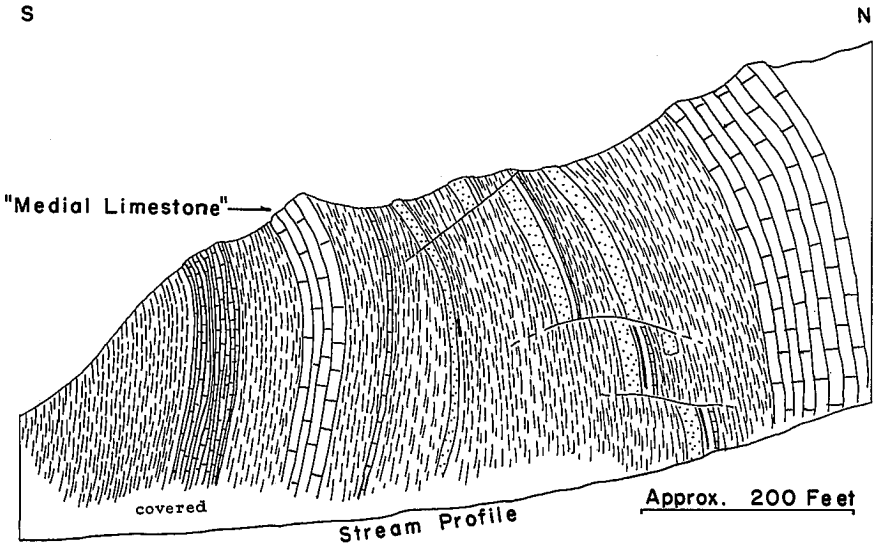
Others who have studied or measured the formation elsewhere include: Nolan (1935) in the Gold Hill district, Utah; Bissell and Hansen (1935) discussed the Mississippian-Pennsylvanian boundary within the formation, and Robertson (1940) discussed the selenium content of the shales. Baker (1947) measured the unit in the Provo Canyon region, and Bullock (1951) in the Pelican Hills and Lake Mountain. Hebertson (1950) was concerned with the origin and composition of the formation, and Calderwood (1951) measured a section in the Cedar Valley Hills. McFarland (1955) measured a complete section in West Canyon of the Oquirrh Mountains, and Croft (1956) studied the formation in the Onaqui Mountains. Pitcher (1959) reported an incomplete section in the Traverse Mountains, and Young (1955) mapped an incomplete section in the Lakeside Mountains. Ornelas (1953) and Hyatt (1956) studied the clays of the formation. Rigby (personal communication) and students discovered one coal bed in Soldier Canyon in 1960, and Tidwell (1962) discussed the flora of the Lake Mountain area.

Field Work

Field work commenced in October 1962 and continued through the Spring of 1963 and consisted of measuring and sampling, in detail, a stratigraphic section with a six-foot steel tape and Brunton compass. Shallow trenching was necessary through approximately two-thirds of the section to insure accurate samples and measurements. Much of the shale shown in text-figure 2 required trenching.

Laboratory Work

Thin sections of quartzites, limestones, nodular siltstones, and shales were prepared and examined. Shales required the use of epoxy resin as a bonding cement. Differential thermal analyses were made on underclays, coals, and shales for determination of mineral content and correlation. Insoluble residues were prepared with HCl, washed, dried and weighed to determine insoluble fractions. and then studied. Fossils were prepared and identified using standard techniques.



TEXT-FIGURE 2.—Cross-section of measured spur.

Acknowledgments

The writer expresses sincere thanks to Dr. J. Keith Rigby, committee chairman, for his direction, assistance with illustrations, and review of the manuscript. Thanks are also extended Dr. Harold J. Bissell, who served as a thesis committee member, and Olivia Villalobos, who typed the manuscript.

STRATIGRAPHY

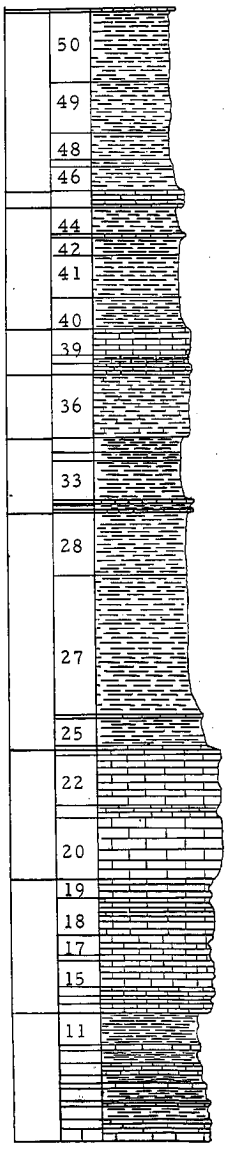
The Manning Canyon Shale is considered latest Mississippian, Chesteran and Springeran. The boundary between the series in Soldier Canyon is not sharp, but is often placed at the top of a persistent marine limestone known as the "medial limestone." The top of this limestone is 484 feet above the base of the formation as measured by Moyle (1958), and it marks the final open normal marine environment of deposition in the formation. The cyclothems studied are stratigraphically above the "medial limestone" unit.

In Soldier Canyon the total Manning Canyon Shale measures 1559 feet (Moyle, 1958, p.8); part of the middle third of the formation is the object of this study.

A detailed section totaling 285 feet was measured beginning below the base of the "medial limestone" and extending up section to a prominent, dense, unfossiliferous limestone, on the north slopes of Soldier Canyon, (Text-fig. 3). The section consists of four main gross subdivisions, and 189 units. The four subdivisions include a lower marine limestone-shale sequence-100 feet thick, a lower coal cyclothem-63 feet thick, an upper coal cyclothem-26 feet thick, and an upper partial cycle-96 feet thick. (Appendix A, measured section).

Lower marine limestone-shale sequence.—The measured section begins ten feet below the "medial limestone" ledge in a series of alternating shale and lime-

TEXT-FIGURE 3.—Measured stratigraphic section of the middle third of the Manning Canyon Shale, Soldier Canyon, Utah. Vertical scale: one inch equals fifteen feet.



Ls, red-purple, skeletal, hash, one inch bed.

Sh, light gray to green, orange mottling, calcareous, clayey, thin laminae to 1/2" platy beds, weak, few low outcrops, nodular undulating bedding at top, unfossiliferous.

Ls, orange-brown, laminated, shaly.

Sh, medium gray to dark green, non-calcareous at base, becomes lighter gray, calcareous, clayey, and waxy toward top; Limestone in center, brown, shaly with shell fragments.

Ls, brown, thin bedded, fossils at base and top Composita, Spirifer, bryozoans, and crinoids.

Siltst, brown, calcareous, with some shaly limestone, orange and black laminated, Spirifer at top.

Sh, with thin limestone at base; sh, medium gray to black, laminae, non-calcareous, unfossiliferous; limestone is thin, brown, shaly, crystalline.

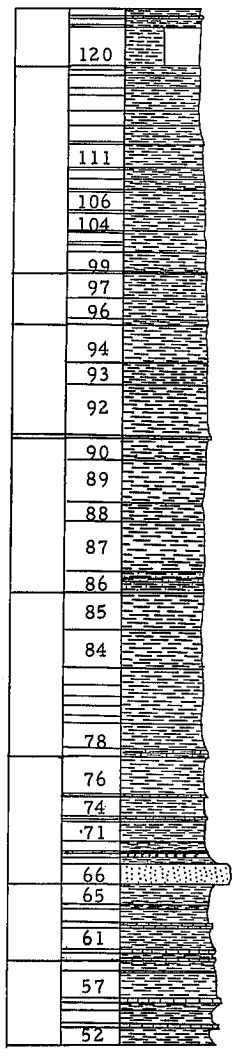
Sh, dark gray to black, paper thin to laminated, 2" calcite bed two feet above base overlain by 12 feet of black non-calcareous shale with spheroidal nodular concretions, somewhat silty, weak slope former, interval unfossiliferous.

Ls, "medial limestone", medium gray, medium to thick bedded, massive ledge, calcite veinlets, contains brachiopods, crinoids, encrusting and fenestellid bryozoans, solitary corals 3' below top, which is capped by brown 3" limestone.

Ls, "medial limestone", medium gray, thin to medium bedded ledge, irregular bedding with shale partings, radiating calcite crystals unit 18, contains brachiopods, pelecypods, crinoids, and solitary corals at top.

Ls, and sh, alternating thin bedded limestone and weak thin laminated shale; ls, light to medium gray, abundantly fossiliferous: brachiopods, Spirifer, Composita, Marginifera, pelecypods, Pinna, bryozoans, Polypora, Fenestrellina, Archimedes, crinoids, occasional trilobites and solitary corals.

(TEXT-FIG. 3, CONT.)



Sh, brown, fissle to earthy and gypsiferous, poorly exposed, becomes silty and calcareous toward top.

Sh, and siltstone; Shale varies from dark gray to light gray and from slightly calcareous at the base to non-calcareous toward the top. Pelecypods, Yoldia? are present near base on weathered surfaces. Silt increases toward the top. The siltstones are rather barren of fossils. A thin, brown, shaly limestone is at the base, with pelecypod fragments.

Sh, medium gray to green, non-calcareous, nodular, becomes silty, Yoldia on weathered surfaces, very irregular bedding.

Sh, dark gray to green, slightly calcareous, thin and platy, nodular irregular bedding, possible pelecypod impressions, Yoldia?

Ls, brown, fine grained, abundant pelecypods.

Sh, medium gray to green, non-calcareous, very fissle at base becoming thin platy toward top; Siltstone at base, orange and black mottled, slightly calcareous, nodules are not calcareous, no definite fossils in this interval.

Sh, with ls; Shale is green to black, non-calcareous, very fissle to platy, contains occasional nodules, Yoldia? impressions, limonite replaced, near top. Ls, at base, shaly to silty, brown, with calcite veinlets.

Sh, black, waxy, with nods, plants, pelecypods; and ls, sandy to silty, nautiloid, pelecypods.

Sh, roof, gray, nodular, plants, Yoldia, limonite.

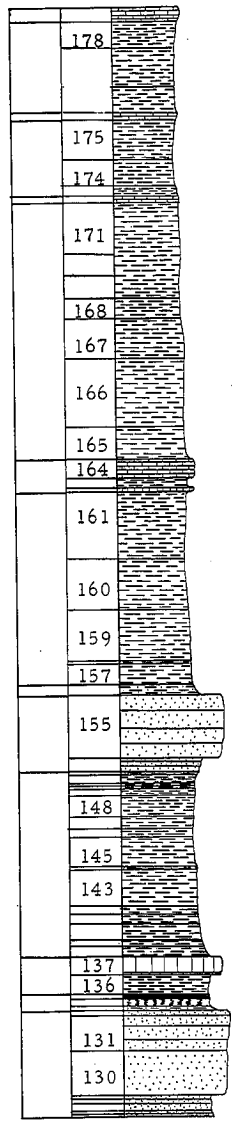
Coal, lignite; and unbedded underclay, brown.

Qtzt, brown, hard, fine grained, crossbedded.

Sh, and interbedded ls, shale is dark green to black, noncalcareous thin and fissle with nodules. Ls, medium brown, irregular, possible fossils.

Sh and ls, light gray to red, weak slope, thin platy limestones to fissle paper shales, shales, clayey to earthy; zone unfossiliferous.

(TEXT-FIG. 3, CONT.)



Ls, gray, dense, thin bedded, calcite veinlets.

Sh, red-brown, calcareous, clayey, mostly covered; weak slope forming zone, no fossils.

Ls, light brown, silty, thin bedded.

Sh, red-brown, calcareous, earthy at top and base; middle 2' black, irregular, non-calcareous.

Ls, gray, very fine grained, thin bedded.

Sh, red-brown to green, mostly calcareous, somewhat earthy and waxy, paper thin to 1/2 inch beds, weak slope zone, poor exposures, no fossils in this shale interval.

Ls, light brown, fine grained, calcite stringers, thin bedded, unfossiliferous.

Sh, gray to brown at top, basal 5 feet dark gray to black, waxy, fissle, contains nodular concretions; some limonite concretions at base; interval is non-calcareous.

Sh, sandy to silty, brown, thin, platy.

Qtzt, buff, brown and orange mottled weathering, hard, dense, fine grained, well sorted, medium bedded, silica cemented, forms resistant ledge. Few thin beds at base.

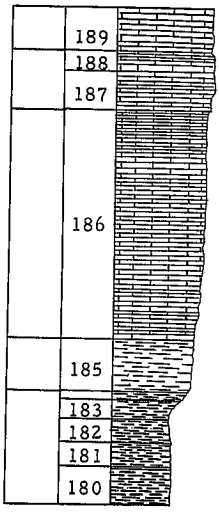
Sh, black to medium gray, mostly non-calcareous, fissle to thin laminae, contains spheroidal nodules throughout, non fossiliferous. Few thin silty and limy beds.

Ls, black, dense, ostracods, gastropods; underlying roof shales, brown and gypsiferous.

Coal, brown, lignite, banded, with black underclay.

Qtzt, buff, hard, fine grained, well sorted, thin bedded at base becomes thick at top, ledge, crossbedded, contains orange limonite mottling, silica cemented.

TEXT-FIGURE 3 (CONT.)



Ls, medium gray, dense to lithographic, laminate to thin bedded, very undulatory.

Ls, medium gray, thin bedded but weathers in massive ledge, dense, undulatory.

Ls, medium gray to tan, weathers light gray to tan, fine grained, thin bedded, beds vary from 1/2" to 4", very platy low outcrops, no fossils.

Sh, tan, calcareous, earthy and clayey, thin laminae; some beds are light green and weather tan.

Sh, red-brown, calcareous, earthy, varies from soft to hard laminae; 3' above base shale is black non-calcareous, 2' chippy unit, no fossils; weak slope zone.

stone. The sequence below the measured interval is mostly platy limestone and shale, thus the measured section begins in marine sediments. The basal ten feet of the section is abundantly fossiliferous containing brachiopods: *Spirifer, Composita, Marginifera;* pelecypods: *Pinna;* crinoids; bryozoans: *Fenestrellina, Polypora, Archimedes;* and occasional trilobites and solitary corals.

The "medial limestone" is a massive, medium to thick bedded, 20-foot resistant ledge, and is a key marker unit for lateral correlations. The lower ten feet is very irregularly bedded, medium gray to blue-gray, light gray weathering limestone with some interbedded shaly partings. Twelve feet above the base of the ledge in unit 18, unusual authigenic calcite crystals occur in a dark gray limestone. These crystals are randomly oriented and radiating; they weather-out in petal-like shapes. The upper ten feet of the "medial limestone" is more massive and thicker bedded.

Fossils occur throughout the limestone but are not as abundant as in the beds below. Brachiopods, pelecypods, crinoids, bryozoans, and solitary corals are represented (Pl. 3, fig. 4). Solitary corals appear in a band three feet below the top, which is capped by a three-inch brown limestone.

Overlying the "medial limestone" is a slope-forming shale series approximately 68 feet thick. The immediately overlying 14 feet is black fissile shale, which is non-calcareous, unfossiliferous, and highly carbonaceous. Nodular siltstone concretions occur throughout this and most other shale units and are typically very lenticular, dense, black, non-calcareous, and generally unfossiliferous. These nodules are similar to the ironstone concretions of the mid-continent shales. The black shale grades upward into gray, calcareous shale with a few interbedded thin limestones.

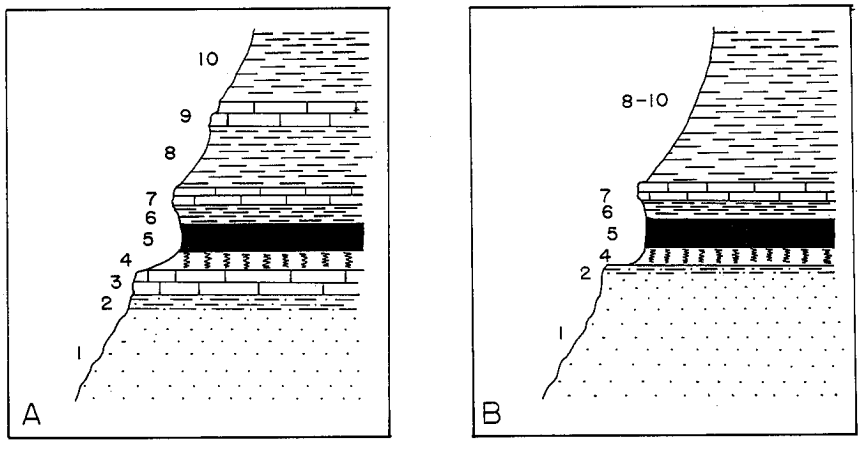
Three interbedded limestone units in this shale sequence deserve mention because of their fossil content. Unit 37, 60.5 feet above the base of the section, is a nine-inch, finely crystalline, brown limestone containing abundant *Spirifer* and *Composita,* and broken pelecypod fragments. Unit 39, located eight inches above unit 37, is a two foot, thin bedded limestone with brachiopods, bryozoans,

and crinoid debris. Unit 51, 89.3 feet in the measured section, is a one-inch skeletal limestone consisting of brachiopod and pelecypod hash. It is a reddish-purple bed as is the overlying 15 inches of calcareous shale. These three units are the only fossiliferous units in the shale sequence.

Lower coal cyclothem.—The lower cyclothem is 63 feet thick and is partially developed, containing only five members. The standard fully developed cyclothem of the mid-continent contains ten members (Text-fig. 4). Very few cyclothems, however, are fully developed and Weller (1957, p. 330) lists the five members generally present in a simplified sequence as follows: basal sandstone, underclay, coal, limestone, and shale. The lower five standard members are non-marine deposits, while the upper five are considered to be marine; thus the cyclothem is divided into two hemicyclothems. In the Illinois region the two hemicyclothems are about equal whereas to the east in the Appalachian area non-marine strata dominate. In Soldier Canyon the marine sequence predominates in both cyclothems.

The lower cyclothem consists of a basal quartzite, 18 inches thick, a thin two-inch sandy shale, an eight-inch underclay, a one to two-inch weathered coal seam, and two feet of roof shale which grades upward through a few limestone beds into a thick overlying shale sequence.

The basal quartzite is a fine grained, well sorted, light gray to buff, brown-weathering resistant ledge former which is somewhat crossbedded near the base. This unit is a protoquartzite, containing 85 percent sub-angular to sub-rounded quartz grains, ten percent dark minerals mostly limonite, two percent ferromagnesium minerals, and one percent zircon and other heavy minerals (Pl. 3, fig. 1). Feldspar is noticeably absent. Cementing material is principally silica. This quartzite varies in thickness, locally up to four feet thick in outcrops to the west (Pl. 2, fig. 3). Down slope to the east calcirudite, flat-pebble beds are present beneath the quartzite in a thin lens.



TEXT-FIGURE 4.—A. Standard idealized mid-continent cyclothem (after Weller, 1957, p.330). B. Generalized Soldier Canyon upper cyclothem. Basal sandstone 1, sandy shale 2, lower limestone 3, underclay 4, coal 5, roof shale 6, middle limestone 7, middle shale 8, upper limestone 9, upper shale 10. Units 1-5 are considered nonmarine and units 6-10 are marine.

Sandy shale overlying the quartzite is a weak unit which probably is not extensive. It grades upward into a black clay shale which in turn grades into gray to brown earthy underclay. The underclay is about six inches thick, impure, sticky, unbedded, and contains a few poorly preserved root markings.

Coal of the lower cyclothem is a one to two-inch lenticular lignite or sub-lignite. The seam is highly weathered thus obscuring any structures. The coal appears to thicken to about six inches at the Jenny section one-quarter mile to the west. These four members, the quartzite, sandy shale, underclay and coal are all part of the fresh-water phase. The remaining fifth and possible sixth member would represent the marine cycle.

Overlying roof shale is a black, thinly laminated to fissile, nodular shale. Nodules are somewhat silty and contain pelecypod and ostracod fragments along with macerated plant remains (Pl. 3, fig. 2). Fossils are replaced by limonite and are poorly preserved. The roof shale is 28 inches thick and is overlain by a thin silty and sandy limestone; unit 75. The sandy limestone contains nautiloids, indicating a marine to brackish- marine environment.

Roof shale grades gradually into an upper shale sequence which is 60 feet thick. A two-inch limestone, unit 91, occurs 35.3 feet above the base of the quartzite, and contains broken brachiopods and pelecypods. Unit 95, 42.2 feet above the base of the cyclothem, is a four inch siltstone bed containing *Yoldia?* fragments on weathered surfaces. The fossils appear to be concentrated on the upper and lower bedding planes.

Upper coal cyclothem.—The upper cyclothem is moderately developed containing seven members. This cyclothem is only 26 feet thick, 15 feet of which is marine. The lower four members are fresh-water deposits, consisting of eight and one-half feet of basal quartzite, two inches of sandy to silty shale, six inches of black shaly underclay, and four to five inches of banded coal (Pl. 2, fig. 2).

The quartzite, the first non-marine deposit, is very similar to unit 66, the basal quartzite of the lower cyclothem. It is a little less clean, with increased orange limonite mottling, and is very hard, forming a resistant medium-bedded ledge (Pl. 2, fig.1). The top six inches is a friable sandstone probably a result of recent weathering of the quartzite.

Friable sandstone grades upward into a dark gray sandy shale which is gradational with the overlying black waxy underclay. The underclay is bedded as shale in part, and is very high in carbonaceous as well as clay content. No fossils or root fragments were observed in this underclay.

Coal occurs as a four-inch banded lignite to sub-bituminous bed. This coal pinches out in the faulted upper cyclothem on the crest of the measured spur. It reappears in the Jenny section as a lenticular seam. Underclay and the overlying roof shale and middle limestone bed are persistent where the coal is missing. Gypsum is associated with the coal and roof shale.

The roof shale is interbedded brown, earthy, and gypsiferous shale and thin shaly limestones totaling 13 inches. Roof shale thickness is variable, where the coal is missing roof shales are very thin.

Immediately overlying the roof shale is a twelve-inch limestone bed known as the middle limestone, member seven of Weller (1957). It is black, dense, and is cut by minute vertical calcite and graphitic veinlets. It is a relatively pure limestone (11.3 percent insoluble, Appendix B) but the residue is highly carbonaceous. The unit contains a small fauna of pelecypods, ostracods, and low spired gastropods. Steinkerns of ostracods and gastropods were found in residues as

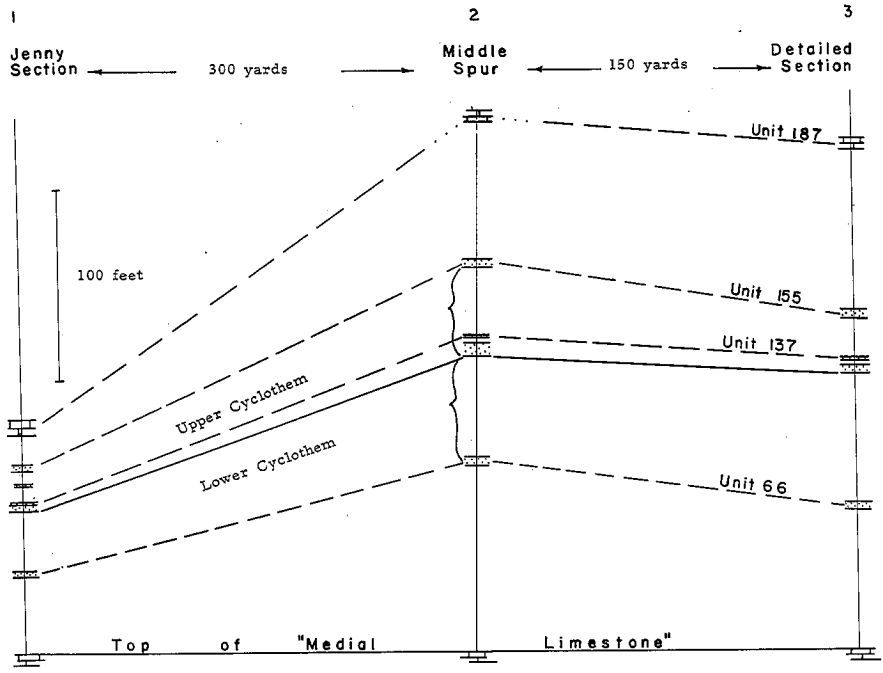
microfossils (Pl. 3, fig. 3). This limestone is a key marker unit in the upper cyclothem and is traceable to the west (Text-fig. 5). It is readily recognized by its consistent thickness, stratigraphic position, and weathering habit.

The remaining member of the upper coal cyclothem is an upper shale sequence. This unit is black, nodular, non-calcareous, and unfossiliferous. It is about 15 feet thick and occupies a gully between the upper two quartzites.

Upper partial cycle.—The final subdivision of the measured section is 96 feet thick and immediately overlies the upper coal cyclothem. A basal quartztie again forms a prominent resistant unit and is similar to the two lower quartzites in composition. It is thick bedded and totals four feet, and is best exposed on the ridge crest.

Ten inches of brown silty to sandy shale overlies the quartzite and may correspond to the sandy shale member of the standard cyclothem. Above this unit is six feet of black, waxy, plastic, shale, high in carbonaceous content, which grades vertically into a brown to gray, silty to calcareous shale. Sixty seven feet of shale is present in this partial cycle. A few thin silty limestones are present but do not contain fossils.

The final 25 feet of the measured section is composed of thin bedded blue-gray limestone which is dense, almost lithographic. Bedding is thicker in the upper seven feet but is undulatory throughout, especially at the top. Lack of fossils and the dense fabric point to a hypersaline bank, as a possible environment of deposition. It is evident that conditions were not present for development of coal or underclays in this cycle. Perhaps subsidence occurred rapidly eliminating possible swamp development.



TEXT-FIGURE 5.—Correlation diagram, Soldier Canyon, Utah.

CONCLUSIONS

Environment of Sedimentation

Basal quartzite.—Three quartzites are present in the Soldier Canyon section and each occupies the basal position of a sedimentary cycle (Text-fig. 5). These beds compare with the basal sandstones, unit one of the standard mid-continent cyclothem which are typically channel, bar, or alluvial deposits (Text-fig. 4).

Soldier Canyon quartzites indicate uplift in the adjacent source regions and slight to moderate regression of the sea; clastic sedimentation exceeded rate of subsidence. They are probably locally extensive deltaic deposits since they show little variation in thickness laterally and are not channeled; no obvious unconformities exist at the base of the quartzites (Pl. 2, fig. 1).

Maturity is indicated by lack of feldspar, though this may be a result of low-feldspar source rock, rounding of the quartz grains, good sorting, and lack of rock fragments. The three quartzites are lithologically very similar and indicate similar conditions of source, transporation, and deposition. All are tightly cemented by silica, indicating an abundance of soluble silica in the streams. Cross-bedding is apparent near the base of the quartzites, reflecting deltaic distributary deposition.

Transgression of the sea, peneplanation of the source area, diminution of stream competency, or sedimentary diversion due to barriers may account for the cessation of clastic sand deposition.

Fossils were not found in the quartzites, although wood fragments and logs have been reported to the south and east in central Utah (Rigby, personal communication).

At the close of sand deposition the region was near base level, topography being uniformly reduced—ideal conditions for development of soils, clays and swamp deposits.

Sandy shale.—Unit two of the standard cyclothem is poorly developed in Soldier Canyon. Thin sandy to silty shales occur above each of the three quartzites and range from two to six inches thick. These units represent the waning phase of coarse clastic deposition, very fine sands grading vertically into fine clastics, silt and clay.

Lower (fresh-water) limestone.—This member is absent in the Soldier Canyon section. Sufficient water depth and calcium carbonate were not present for the development of this unit, number three in the standard sequence.

Underclay.—Underclay, unit four, is one of the most characteristic beds of the mid-continent cyclothems. Soldier Canyon underclays are present above the lower two quartzites but undeveloped above the third or highest quartzite of the measured section.

Underclays exposed in the section are thin, irregular to unbedded, and range from black clayey shales to gray or brown, earthy, sticky clay. Occasional root markings occur, though poorly preserved.

Nearly stable subaerial conditions initiated the development of soil surfaces without accompanying marsh conditions. The area supported vegetation but was adequately drained, and clay soils were produced.

Underclays are generally associated with overlying coal seams, but such clays are present in the measured section without overlying coal beds as in the upper cyclothem. The upper coal pinches out on the ridge but is present to the east above a black underclay. Underclay and associated overlying beds are persist-

ent laterally where coal is missing. These clays probably developed on partially drained surfaces covered with vegetation. Lack of standing water allowed complete plant decay. Underclays, however, are only a step away from swamp development.

Underclay of the lower cyclothem is gray to brown, earthy to very plastic, sticky, clay. The upper cyclothem underclay is rich in organic matter, black, irregular, clayey, waxy shale. The climate was probably warm and moist during underclay development, producing abundant vegetal cover. A few plant fragments are present.

Differential thermal analysis failed to indicate any particular clay mineral. Impurities masked any definitive reaction curves in the specimens analyzed.

Coal.—Coal is member five of the fresh-water hemicyclothem. All of the above discussed members are in the fresh-water phase of a cyclothem.

Soldier Canyon coals are thin, brown to black, banded, lignite to sub-bituminous deposits. They are lenticular, but are locally extensive over one-quarter mile of outcrop.

Coal of the lower cyclothem is one to two inches thick and is highly weathered (Pl. 1, fig. 2). Two spurs to the west this coal may be as much as six inches thick. This seam is sub-lignitic to lignitic.

The upper coal is four to five inches thick, brownish black, banded lignite to sub-bituminous (Pl. 2, fig. 2).

Development of peat in swamps, and subsequent burial and metamorphism to coal require several special conditions. Marsh development indicates reduced topography, such as in the Dismal Swamp of Virginia and North Carolina, and steady slow influx of fresh water. Typical luxuriant Mississippian-Pennsylvanian floras developed, grew, and died in the quiet waters of the coastal swamps. Dead and partially decayed vegetable matter acted a giant sponge to retain and soak up moisture. Biochemical processes of putrefaction and autolysis proceeded in the anaerobic swamp bottoms, thus total plant decay was prevented and peat accumulated.

Rate of peat accumulation depends on climate and vegetation. White (1913, p. 62) states that it generally requires 10 to 20 feet of peat to produce one foot of bituminous coal and roughly in time units, 100 years. Soldier Canyon coals would require approximately five to ten feet of accumulated peat. Vegetation and water-cover depth must necessarily keep pace with each other over a period of time to produce even five feet of peat.

Climate was fairly uniform, generally warm, moist and wet. Seasonal variations were apparently negligible, and rainfall was moderate to heavy but uniform year-round. Flooding would silt-up and choke the swamps in addition to diluting the swamp waters thus aerating, oxygenating, and accelerating plant decay. Topography was likewise uniform and low as evidenced by the lack of clastic deposition. Stable, near shore, uniform environments existed during development of coal swamps.

Lower shale (roof shales.)—Unit six of the standard mid-continent cyclothem is known as the lower or roof shale. It is generally erratic in development and is not present in all cyclothems. Some coals are found directly overlain by limestones (Weller, 1957, p. 330).

Roof shales are developed in the Manning Canyon Shale cyclothems above the two coals of the cyclothems and possibly above the sandy shale unit of the partial cycle at the top of the measured section. They are variable units ranging

from black nodular shale to earthy brown gypsiferous zones. They reflect various brackish to marine environments, from the deepened, partially reducing, high organic environment in the lower cyclothem to the shallow, aerated, restricted, oxidizing, environment of the upper cyclothem.

Pelecypods, ostracods, and plant fragments are found in the roof shales. Capping 28 inches of roof shale in the lower cyclothem is a thin limestone containing nautiloids, suggesting nearly normal marine conditions.

Roof shale of the upper cyclothem is 13 inches thick and consists of gypsiferous and calcareous brown earthy shale, and brown shaly limestone. Environment of this unit was probably quite shallow marine to brackish, circulation being restricted at times. This may account for the presence of gypsum in these roof shales. The gypsum may in part be due to a post diagenetic introduction due to solution and weathering.

The upper partial cycle may or may not contain roof shale, if so, it would be represented by a black, plastic, hard shale.

General transgression of the sea with attendant basin subsidence accounts for the lower shale deposits and initiates the marine hemicyclothem, which in both cyclothems is thicker than the fresh-water hemicyclothem.

Middle limestone.—Unit seven of the standard cyclothem section is represented by a single 12 inch bed in Soldier Canyon which occurs above the roof shales of the upper cyclothem. It is a dense, black, carbonaceous nearly pure limestone. Fauna of this limestone consists of small pelecypods, ostracods, and low spired gastropods, observed only in thin sections and residues as microfauna (Pl. 3, fig. 3).

This unit represents a deepening of the basin and a return to more nearly normal marine salinities. Aquatic vegetation may account for the high carbonaceous content and black color of the limestone (Weller, 1957, p. 350). Its absence in the lower cyclothem denotes that the basin was not subsiding fast enough to allow deposition of near normal marine limestone.

Middle shale.—Standard cyclothem unit number eight is the middle shale of the upper or marine hemicyclothem. It is a lower black fissile to chippy shale, and an overlying gray calcareous shale. Delineating this member in the Soldier Canyon section is difficult since gradational effects obscure contacts. Black shales are not well developed in the lower cyclothem. In the upper cyclothem, the middle shale overlying the ostracod-limestone is a black non-calcareous somewhat nodular shale. It is gradational with the upper shale, unit ten, the last member of the marine hemicyclothem.

The middle shale may be present above the sandy shale of the upper partical cycle. If so, it is gradational with a roof shale, where six feet of black shale grade upward into gray to brown calcareous shales.

This member was probably deposited as organic-rich colloidal slimes with subsequent extensive compaction and dehydration. Fossils are rare and as Weller (1957, p. 351) points out, this may be due to prolific growth of seaweed which limited current circulation thus removing oxygen and creating an unfavorable benthonic condition. The seaweed may also account for the high organic content of the shales.

Upper limestone.—Standard unit nine represents culmination of marine to open marine conditions. In the two coal cyclothems this unit is missing or represented by very thin units. Normal marine conditions were not established. The limestone

at the top of the measured section may correlate with this standard unit but it is unfossiliferous; the limestone is closer to a precipitated hypersaline deposit.

The "medial limestone" unit at the base of the measured section closely fits the upper limestone category. If it is the upper limestone of a marine hemicyclothem this would make it part of a lower incomplete cycle. Abundant marine fossils occur in the unit and especially in the platy underlying ten feet. The ledge of the "medial limestone" is not as fossiliferous as the thin beds below, but contains brachiopods, pelecypods, crinoids, and near the top a band of solitary corals. The corals probably required relatively warm, clear, silt-free, shallow waters.

Upper shale.—The tenth unit of the standard cyclothem is generally thick, uniform and unfossiliferous.

Change from limestone deposition to fine clastics was fairly sudden in the measured section. The sea retreated and fine clastics, mostly silt, were brought into the basin. Mild uplift had probably begun in the source regions. Fine clastics grade upward into the coarser clastics of the basal quartzite member of the overlying cycle. This unit represents a transition between marine and nonmarine phases.

Influx of turbid silty waters established relatively unfavorable conditions for animal life. Variations of influx might explain the occasional thin pelecypod-bearing siltstones.

Above the "medial limestone" the upper shale is present and totals 60 feet. It contains a few fossiliferous limestone beds indicating momentary return of life to the region. Shales range from black chippy shale to gray and brown calcareous units. Silt, however, increases toward the top indicating the advent of sand deposition, and continued regression of the sea.

In the lower cyclothem the upper 50 feet of shale and siltstone may represent this upper shale member. Concretions are particularly abundant in this interval, and a few beds contain pelecypods on weathered surfaces. The upper cyclothem does not show this unit as well but it is probably present in the uppermost five feet of the cyclothem. In the overlying partial cycle this unit is missing.

APPENDIX A

A section of part of the Manning Canyon Shale exposed on the north wall of Soldier Canyon, one-half mile above the mouth, on the third spur east of the Jenny prospect tunnel. The section is located in the SW¼, NE¼, Sec. 33, T. 4 S., R. 4 W., Tooele County, Utah, five miles southeast of Stockton, Utah.

Only the cyclothem stratigraphy is presented, beginning at the base of the lower cyclothem, unit 66, and extending to the top of unit 159 of the upper partical cycle. The complete section is on file in the Geology Department of Brigham Young University.

Mississippian

Manning Canyon Shale

Unit No.	Description	Thickness in inches	Total feet above base
159	Shale: black, weathers same, waxy, non- calcareous, very thin to paper thin, "ironstone" concretion at 29", orange limonite and calcite in concretion	48	200.8
158	Shale: black, weathers gray, grades into one-half inch vienlet of calcite, possible plant fragments in shale	1	196.8
157	Shale: black, weathers same, waxy, paper thin partings,		

APPENDIX A (CONT.)

	non-calcareous, very fine grained, with brown limonitic nodules at base	18	196.7
156	Shale: light gray to buff, weathers light brown, very silty to sandy, ¼" beds, non-calcareous, silty and sandy at base, nodules at 3"	10	195.2
155	Quartzite: light gray to buff, weathers tan-brown with limonitic spots, medium to thick bedded, one and three foot beds, forms resistant ledge, fine to medium grained, well sorted, non-calcareous, somewhat cross - bedded at base, very hard	48	194.3
154	Quartzite: medium to light gray, weathers tan-brown hard, resistant ledge former, slightly calcareous, silty, thin bedded, marks base of upper partial cycle	12	190.3
153	Siltstone: brown, weathers same, somewhat shaly and nodular	2	189.3
152	Shale: black, dense, non-calcareous, nodular irregular bedded, top 2" is gray clay shale	10	189.2
151	Clay: medium gray to light green, weathers same, very waxy and clayey	1	188.3
150	Shale: medium gray to light green, clayey, and non-calcareous	2	188.2
149	Siltstone: brown, weathers light brown, slightly calcareous, thin 1" beds, hard and compact	6	188.1
148	Shale: nodular, green to brown, weathers brown, slightly calcareous, ¼" to 1" beds	18	187.6
147	Shale: medium gray to dark green, weathers mottled gray-brown, non-calcareous, very thin to ½ inch beds, irregular	12	186.1
146	Shale: light green, weathers brown, calcareous, very thin to ¼" platy beds, somewhat nodular	9	185.1
145	Shale: medium gray to green, weathers gray and brown, slightly calcareous, ¼" to paper thin; 1" at top siltstone medium gray, weathers brown, slightly calcareous, compact	28	184.3
144	Siltstone: medium gray, weathers light gray, nodular bed, lens pinches out within two feet, very fine grained	3	182.0
143	Shale: black, weathers medium gray, non-calcareous, 1" nodules at base and at 15", paper thin to ¼" beds	30	181.8
142	Shale: black, weathers gray, waxy, non-calcareous, ⅛" beds, chippy, hard	6	179.3
141	Shale: black, weathers gray, waxy, clayey, ½" to ¼" beds, contains plant fragments	9	178.6
140	Shale: medium gray to gray, weathers light gray, nodular, irregular 1" to ½" beds. non-calcareous	14	178.0
139	Shale: black, dense, weathers gray to brown, silty, lacks fissility, somewhat nodular, non-calcareous, waxy and clayey, ½" beds	7	176.8
138	Shale: medium to light gray, weathers same with orange mottling, very thin to paper thin bedding; Limestone, brown, shaly at base	8	176.3
137	Limestone: black, weathers brown to gray, dense, weathered surface shows vertical fine black graphitic? seams, resistant ledge, 10½" and 1½" beds, laterally persistent-key marker bed for upper cyclothem, thin-section reveals ostracods, pelecypods, and low spired gastropods; brackish-marine	12	175.6
136	Shale: roof shale, consists of the following: Top 2½" shaly limestone, fine grained; 3" shale, red, earthy; 2" shaly limestone, light brown; 3½" shale,		

APPENDIX A (CONT.)

	medium brown, gypsiferous earthy to paper thin; 2" shale, red to red brown, gypsiferous, paper thin, earthy	13	174.6
135	Coal: brown to dark brown, lignite, banded, associated gypsum, lenticular; some limonite on weathered surface, near vitreous luster	4	173.5
134	Underclay: black to dark gray, irregular bedded to unbedded, waxy and highly carbonaceous	6	173.2
133	Shale: dark gray, silty to sandy, non-calcareous	2	172.7
132	Sandstone: light gray, weathers brown, fine to medium grained, subangular to subrounded grains, noncalcareous, semifriable at top,	6	172.5
131	Quartzite: light gray to buff, weathers brown, fine to medium grained, subangular to subrounded, orange limonite mottled spots thin bedded—6" to 1', vertically jointed and crossbedded in part, resistant ledge	33	172.0
130	Quartzite: light gray to buff, weathers brown, dense, silica cemented, thick bedded, single 41" bed, crossbedded at base, limonite occurs as weathered spots, fine to medium grained and subangular to subrounded	41	169.3
129	Quartzite: same as unit 130 except slightly calcareous	5	165.8
128	Quartzite: light tan, weathers brown, unit consists of 2" of quartzite and 3" of sandstone, weak with very thin partings	5	165.4
127	Quartzite: as unit 125, rippled upper surface	4	165.0
126	Quartzite: as unit 125, but thinner beds ¼ to 1", some sandy shale partings	6	164.7
125	Quartzite: light tan, weathers brown, slightly calcareous, very fine to fine grained, with calcite veinlets, 1-2" beds, marks base of upper cyclothem	2	164.2
124	Shale: light brown, weathers same, silty, although dominantly clay shale	7	164.0
123	Shale: light gray to brown, weathers same, silty	1	163.4
122	Shale: light brown, weathers same, noncalcareous, very thin to paper thin	7	163.3
121	Siltstone: light brown, weathers same, calcite vienlets, irregular ½" to 1" beds	1	162.8
120	Shale: light tan to medium brown, gypsiferous, calcareous, earthy to very thin beds, weathered graphitic soil and limonite present in a lenticular pod	2	162.7
119	Siltstone: light gray to brown, weathers same, calcareous, shaly partings, 1" beds	4	162.5
118	Shale: light gray, weathers same, clayey, contains earthy brown nodules with gypsum, paper shale but in compact beds	12	162.2
117	Calcite: white to yellow-orange, with earthy shale partings	1	161.2
116	Shale: light brown, weathers same, calcareous, very thin to ¼" beds, somewhat earthy	6	161.1
115	Shale: black to dark green, weathers medium gray, hard, thin ⅛" plates, contains nodules near base, lower 4" nodules are laminated brown and gray and calcareous; shale is slightly calcareous	12	160.6
114	Shale: medium gray to brown, weathers light brown, non-calcareous, hard compact ¼" beds but shale parts to near paper thin, contains nodules at very top, nodules are argillaceous to slightly silty, dense, non-calcareous and vary from ¼" to 1" thick and 4" to 6" wide; shale is very irregularly bedded	16	159.6
113	Shale: medium gray and brown mottled, weathers light brown, calcareous, irregularly bedded, may be slightly silty, undulating bedding; varies from paper thin at base to ¼" and ½" beds, 1" irregular nodules	14	158.4

APPENDIX A (CONT.)

112	Siltstone: orange and brown laminated, calcareous, hard 1" ledge, very irregular undulating surface, may be 30% calcareous	1	157.1
111	Shale: light gray to brown, weathers same, non-calcareous, thin-⅜" platy beds, very irregularly bedded, undulating, Pelecypod found 4" above base—one half inch long smooth poorly preserved specimen	21	157.0
110	Siltstone: black, weathers orange-brown, very fine grained, very hard and dense, non-calcareous contains numerous calcite veinlets, irregular bed, pinchs out to west (10 feet) but persistent down slope to east	2	155.2
109	Shale: medium gray to gray and brown laminated calcareous, resistant, compact 4" and 2" beds with shale partings about 1/16 of an inch	6	155.1
108	Shale: medium gray to dark green, weathers light gray to brown, paper thin, low outcrops, non-calcareous to slightly calcareous	10	154.6
107	Siltstone: very fine grained, medium gray, weathers tan, ½" bed, non-calcareous, orange mottled, resistant bed	1	153.8
106	Shale: light brown to green, weathers light gray to brown, weak, slightly calcareous, weathers in thin large sheets 1/16" thick	18	153.7
105	Siltstone. dark gray, weathers medium gray, very fine grained, clayey, dense, hard, with calcite veinlets, orange mottling, resistant 2" ledge	2	152.2
104	Shale: dark green to dark gray, weathers gray, paper thin in compact weak units	14	152.0
103	Siltstone: black to dark gray, weathers tan, very fine grained, hard, cut by calcite and limonite veinlets, resistant ledge	2	150.8
102	Shale: medium gray to greenish brown, weathers tan-gray, orange mottling, slightly calcareous, paper thin	9	150.7
101	Shale: brown and black laminated, calcareous, with orange mottling, irregular thin bedding, ⅛" to ¼", with some paper thin shale	3	149.7
100	Shale: dark green with orange mottling, slightly calcareous	5	149.7
99	Shale: dark gray to black, weathers tan, fissile, brown shaly limestones at 2" and 5", nodular at top, fossiliferous-pelecypods *Yoldia*-like	14	149.3
98	Limestone: medium brown, weathers light brown, shaly, fine crystalline, with calcite veinlets	1	148.1
97	Shale: medium gray, non-calcareous, with nodules and thin limy units, low outcrops	24	148.0
96	Shale: gray to green, weathers brown with orange mottled spots, slightly calcareous, fissile, Pelecypods 10" above base	20	146.0
95	Shale: black, nodular, non-fissile, hard, with calcite veinlets, 1" to 4" bed, contains abundant small pelecypods on upper and lower weathered surface	4	144.3
94	Shale: as unit 96, becomes black and waxy top 1 foot, possible plant or shell fragments	36	143.0
93	Shale: dark gray, weathers gray, calcareous, fissile to nodular at top, ⅜' hard thin plates, 1" to 2" nodules		
92	Shale: dark green to medium gray, slightly calcareous, contains siltstone bed 5" above base with minute calcite vienlets, pelecypod (?) impressions	48	139.1
91	Limestone: brownish-red, weathers tan, very silty, platy irregular bedding, contains abundant small pelecypods	2	135.3

APPENDIX A (CONT.)

90	Shale: medium to dark gray, weathers tan, ⅛" beds, low outcrop, no fossils, slightly calcareous	21	135.1
89	Shale: green to light green-gray, non-calcareous, hard, chippy few nodules	40	133.3
88	Shale: brown to olive green, weathers drab gray, non-calcareous, very thin, few ½" nodules	17	130.0
87	Shale: medium gray to black non-calcareous, thin ⅛" beds, becomes nodular and platy toward top, basal 18" low outcrops	48	128.6
86	Siltstone: gray to black, with orange mottling, slightly calcareous at base to calcareous at top, thin bedded-1", lower 9" is repeated, nodular toward top	16	124.6
85	Shale: medium gray, non-calcareous, platy, with thin black shale partings	38	123.3
84	Shale: gray to green, weathers tan, non-calcareous, contains nodules	36	120.1
83	Shale: black, non-calcareous, earthy, with 1" limestone bed at base, dense, fine grained, cut by calcite veinlets	18	117.1
82	Shale: mostly covered, red-brown, non-calcareous, clayey, with a few thin brown limy units	12	115.6
81	Shale: gray, weathers red-brown, non-calcareous, few compact beds between partings, contains macerated plant fragments and possible broken pelecypods, limonite replaced	9	114.6
80	Shale: medium gray and red, irregular bedding, contains plant fragments, and limonite replaced *Yoldia*-like pelecypods	8	113.8
79	Shale: medium gray, with orange mottling, compact but irregular, contains pelecypods and macerated plants(?)	6	113.2
78	Shale: medium gray weathers light gray, slightly calcareous, platy with nodules, becomes red-brown at top	24	112.7
77	Limestone: black with orange mottling, silty calcite stringers, thin bedded	6	110.7
76	Shale: medium gray, hard, non-calcareous but contains orange mottled calcareous partings, plant fragments, contains silty nodules up to 1" thick	36	110.2
75	Limestone: silty, medium brown, with black-green shale partings, pelecypods and nautiloids present	2	107.2
74	Shale: maroon, fissile, clayey, weathers earthy, gypsiferous(?) partings	18	107.0
73	Limestone: silty, gray to red laminated, slightly fissile but compact 2" bed	2	105.5
72	Shale: light green to reddish-brown, non-calcareous, contains plants and pelecypod fragments	1	105.4
71	Shale: medium to dark gray, hard "sheety", somewhat nodular, contains plant fragments and pelecypods which are replaced by limonite	17	105.3
70	Shale: roof shale, green to dark gray, contains abundant nodules which are silty, non-calcareous, contains plant fragments, and pelecypod valves, nodules contain pelecypods and ostracodes	8	103.8
69	Coal: brown, highly weathered, thin lenticular lignite or sub-lignite, non-banded, varies up to 2" thick	1	103.2
68	Shale and underclay: green, waxy, clayey, shale with orange mottling at base, grades upward into gray, brown, and yellow impure unbedded underclays, macerated plant remains and possible root markings	8	103.1
67	Shale: sandy, mottled green and red, silty to very fine grained, clayey, non-calcareous	1	102.4

APPENDIX A (CONT.)

66	Quartzite: light gray to buff, weathers brown, resistant ledge, hard, fine grained, well sorted, subangular to subrounded grains, silica cemented, weathers with orange limonite spots, crossbedded but not channeled. Base of lower cyclothem	18	102.3

APPENDIX B

Insoluble Residues

Unit No.	Orig. Weight	Final Weight	% Insoluble
23	11.47 gms.	5.92 gms.	51.7%
29	13.70	8.51	50.1
32	21.69	8.11	29.7
36	20.55	17.31	76.1
39	8.38	2.46	29.4
43	10.73	4.94	46.0
47	12.02	8.38	69.7
51	24.52	11.44	32.4
53	14.44	6.24	31.8
56	13.10	6.12	46.7
59	24.62	15.04	21.4
70	24.54	24.15	91.7
72	8.34	1.08	12.9
73	11.56	6.91	46.0
75	12.54	6.35	50.6
77	17.00	11.81	59.4
91	13.01	7.15	54.9
98	11.72	5.55	47.3
121	5.91	3.76	63.7
125	23.73	20.21	85.4
136	4.03	1.25	31.0
137	12.44	4.60	11.3
148	19.25	15.75	81.7
153	13.11	13.80	99.5
162	21.67	5.50	39.5
164	13.85	2.59	18.8
179	19.20	3.55	18.5
189	6.14	0.38	6.2

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Progress Report on Selenium in the Manning Canyon Shale, Central Utah

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ABSTRACT.—More than 20 years ago Beath (1939) located a number of seleniferous areas in the western United States by means of indicator plants. Unusual concentrations of selenium, up to 96 ppm, were reported from shale of the Mississippian Manning Canyon Shale, in Provo Canyon, about 40 miles south of Salt Lake City, Utah.

The present study, limited to 3 months of part-time work, investigates some broad features of concentration, distribution, and lithologic association of selenium within the Manning Canyon Formation, especially at its type section in Soldier Canyon, in the Oquirrh Range, 25 miles northwest of Provo Canyon.

Selenium is present in unusual concentrations in shaly strata throughout the 1600 foot thickness of the formation. High concentrations of selenium are most common in dark-colored, carbonaceous, calcareous, soft, usually gypsiferous and often iron-oxide stained or pyritic shale. Such rocks, interbedded with shaly limestone and nearly pure limestone, carry a mean concentration of 18 ppm with a standard deviation of 8 ppm. Ten to 20 percent of the type section is composed of such rock.

Association of organic matter, pyrite, often oxidized, plus gypsum in some of the most seleniferous beds, indicates possible derivation of selenium from organic matter, and its reconstitution in part as a sulfide, and subsequent oxidation to selenite or selenate.

In hard shale, shaly limestone, and limestone, which constitute a large portion of the Manning Canyon Shale, concentration of selenium decreases to a value below 1 ppm.

The Manning Canyon Shale at Lake Mountain, 20 miles south of Soldier Canyon, supports no selenium indicator plants, a situation wholly different than in Soldier Canyon or Provo Canyon. The Lake Mountain section represents a more terrestrial environment as shown by the greater abundance of coarse clastic rocks and fossil terrestrial plants. A sampled section across one of the better known fossil plant localities yielded the lowest selenium concentrations for shales recorded during the study. Since lithologies at Soldier Canyon are more representative of brackish and marine conditions, it follows that concentration of selenium is more allied to marine or brackish water processes than to terrestrial processes.

Hydrothermal activity, manifestly weak in the portions of the stratigraphic sections studied, may have modified the original distribution of selenium. Evaluation of this effect awaits further study.

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INTRODUCTION

Historical Sketch

In 1934 researchers at the Department of Research Chemistry of the University of Wyoming linked the occurrence of selenium in certain native range plants to toxic effects produced in animals which grazed upon them (Beath, et. al., 1934a). The vegetation in question was confined primarily to Cretaceous or Eocene formations. During the same year, several hundred acres of woody aster and narrow-leafed vetch were observed growing on soils derived from the Chugwater Formation of Permian and Triassic age in central Albany County, Wyoming (Beath, 1934b). Further investigation revealed that two members of the Chugwater Formation supported toxic seleniferous vegetation. A sandstone member near the middle of the formation yielded up to 10 ppm and averaged 2.4 ppm selenium. The second, near the base of the formation, yielded lesser amounts.

Finding selenium in Permian and Triassic rocks greatly enlarged the problem of selenium distribution. Beath and coworkers (1937) traced selenium bearing rocks from the Chugwater Formation in southeastern Wyoming to rocks of equivalent or nearly equivalent age near the western border of the state. Seleniferous rocks were found in the Permian Phosphoria formation as well.

Beath and his colleagues extended their studies into most of the western United States. Many new areas of seleniferous rocks were discovered by recognition of four genera, *Astragalus, Stanleya, Xylorrhiza,* and *Oonopsis,* which were defined as "indicator" plants (Beath, et. al., 1939a p. 259).

> The significance of selenium indicator plants is particularly important in locating seleniferous areas not heretofore recognized in the West. . . We have selected for detailed study certain areas where one or more indicator plants occur. . . The areas include. . . carbonaceous and limy shales of late Mississippian or early Pennsylvanian age in Provo Canyon, Wasatch Mountains, Utah.

The same author in a subsequent paper (Beath, et. al., 1939b, p. 312) states:

The seleniferous shale in Provo Canyon is either late Mississippian or early Pennsylvanian in age. The distinctive odor, characteristic of some seleniferous plants, led Dr. David Love, U. S. Geological Survey, field assistant, to believe that this formation supported seleniferous vegetation. Dr. Love had previously collected seleniferous vegetation in Wyoming under our direction. *Aster glaucus* rooted in these shales was seleniferous. . .

A stratigraphic section, (Table 1) together with the content of selenium associated with each stratum was published (Beath, et. al., 1939a, p. 266)

TABLE 1

Stratigraphic section of a portion of the Manning Canyon Shale at the Canyon Glen Campgrounds, Provo Canyon, Utah.

Bed No.	*Lithology*	*Thickness in feet*	*Selenium ppm.*
20	Shale, chocolate-brown at base, grades to dark black thinner-bedded shale	25	3.6
19	Limestone, forms massive cliff above water flume; is dark black to blue-gray, some sandy limestone present	67½	1.5
18	Shale, very black, has seams of yellowish-brown ferruginous material at very top and at various places in bed	19	34.3
17	Limestone, very shaly, blue to black with brown and yellowish-brown seams	55	0.6
16	Shale, light-brown to dark chocolate-brown, gypsiferous in seams. Forms first shale outcrop near flume	17	25.1
15	Limestone, blue to gray, some shale which is brownish; the bed grades from true limestone at base to sandy and shaly limestone at top	25	12.0
14	Shale, variegated, mainly black with some chocolate-brown colors	24	96.3
13	Limestone, very shaly, dark blue to black	29	2.6
12	Shale, very dark black, thin-bedded	20	7.0
11	Limestone, gray to black; hard	7½	0.5
10	Limestone, very sandy, weathers light-brown	2½	0.5
9	Shale, limy in part, dark black to gray	20	0.6
8	Sandstone, reddish-brown to buff, coarse grains or grit up to 4 mm. in diameter	10½	
7	Limestone, shaly, dark brown, contains numerous small lingulids	11	1.0
6	Limestone, blue to dark black, hard. weathers blue-gray	14	1.0
5	Shale, chocolate-brown, bedding 1 in. to 4 in.; shales are lighter color towards the top, and various fresh—or brackish-water pelecypods present	12	7.5
4	Shale, dark black, carbonaceous in part, and ferruginous in part, bedding less than 1 inch	3	1.8
3	Limestone, dark blue, in part shaly	4½	
2	Sandstone, reddish-brown, very gritty, with coarse fragments up to 5 mm. in diameter	4	1.4
1	Limestone, blue, which extends to bottom of railroad cut, or to railroad tracks	7	0.4
	Total thickness	377½ ft.	

Robertson (1940) investigated distribution of selenium and the possibility of selenium poisoning in Utah. His work dealt with occurrence of selenium in the Manning Canyon Shale and its associated vegetation in part, but no systematic, detailed stratigraphic work was undertaken.

Recent Work

Study of selenium in the Manning Canyon Shale remained for two decades where Beath left it. However, other important studies, helpful to the geo-

chemist, have been made. Moyle (1958) studied the paleoecology of the Manning Canyon Shale. Five sections were measured in central Utah in localities where the formation is best exposed, and five other partial sections, including the Provo Canyon section, were studied as well. The Soldier Canyon section, Tooele County, Utah, 4 miles southeast of the town of Stockton and 25 miles northwest of Provo, is the best exposed and most complete outcrop of the formation. Here the formation is over 1,600 feet thick, and consists mainly of shale and lesser amounts of interbedded limestone. Even smaller amounts of interbedded sandstone and quartzite are present. Clay shale characterizes the lower 600 feet, silty shale and shaly limestone typify the upper 1,000 feet. Fresh, brackish, and shallow, warm marine water conditions are evidenced by typical marine or terrestrial assemblages. Study of the lithologies demonstrates the cyclic nature of deposition with three regressions and two transgressions, punctuated with many minor changes.

Tidwell (1962) described an Early Pennsylvanian flora from the upper shales of the formation. These plants were probably deposited near their site of growth. *Alethopteris, Neuropteris,* and *Calamites* occurred, in order of decreasing abundance. The rock types and flora suggest a fresh or brackish swamp environment.

Prince (1963) studied Mississippian coal cyclothems in the middle one-third of the formation, and measured a detailed stratigraphic section, 285 feet thick. The two described coal cyclothems exhibit characters which compare favorably with mid-continent cyclothems, and probably reflect similar environments.

Purpose and Scope of the Present Investigation

Heretofore investigation of occurrence of selenium in sedimentary rocks of the United States has been conducted primarily by plant and soil chemists (Beath, 1934a to 1946; Moxon et. al. 1938) and by economic geologists studying distribution of selenium and other elements in the Colorado Plateau (Newman, 1962). The former studies were conducted to determine distribution of selenium and the possibility of selenium poisoning of livestock. The latter studies were made primarily to shed light on genesis of uranium deposits.

Discovery of unusually high concentrations of selenium in a considerable portion of the Manning Canyon Formation by Beath (1939a) suggests that distribution of the element, its forms of occurrence, and the environments of its deposition should be studied in detail. Green (1959) reports an average of between 0.3 to 0.6 ppm selenium in shales. Beath (1939a) reports as much as 96.3 ppm in a shale bed 24 feet thick in the Manning Canyon Shale at Canyon Glen Campgrounds in Provo Canyon.

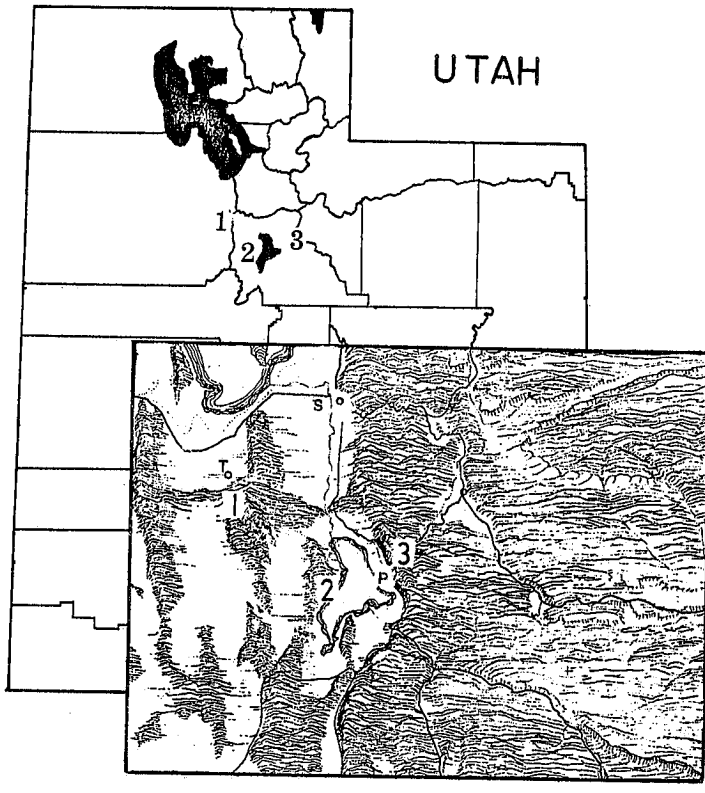
The principal objectives of the present study were the following:

1). To attempt corroboration of Beath's work at the site of the original discovery, i.e., at Canyon Glen Campgrounds, Provo Canyon, Utah.

2). To obtain greater stratigraphic detail in the occurrence of selenium as a function of lithologic type.

3). To isolate, within the most seleniferous strata, the materials which yield the highest concentrations of the element.

4). To use 'indicator" plants, for possible extension of the study beyond the Provo Canyon and Soldier Canyon sections.



TEXT-FIGURE 1.—Index map of sections studied. S, Salt Lake City; P, Provo; T, Tooele; 1, Soldier Canyon in the Oquirrh Range; 2, Lake Mountain; 3, Canyon Glen Campground, Provo Canyon in the Wasatch Mountains.

Field and Laboratory Work

Sections at Canyon Glen Campgrounds in Provo Canyon, at Soldier Canyon, and at Lake Mountain were collected during the summer of 1963. Channel samples, at a depth of 6 inches to as much as 3½ feet, but averaging about 18 inches, were taken across shale beds of the Manning Canyon Shale and details of lithology were noted. Changes in color, texture, mineralogy, and weathering characteristics as well as presence of indicator plants were used for stratigraphic subdivision. In general, only shale beds were sampled; limestones and sandstones were sampled in a few instances but these latter rocks yielded much less selenium than associated shales.

The writer, W. D. Tidwell, and R. W. Moyle, visited the section at Soldier Canyon and Lake Mountain in August 1963.

The method of analysis for selenium in the present study was adapted from Robinson (1934). A 10 gram sample of shale with 10 ml of a 10% solution, by volume, of bromine in concentrated hydrobromic acid, and an additional 10 ml of concentrated hydrobromic acid, were prepared in a Corning C-3440 pyrex glass distilling apparatus. The resulting distillate was collected until 10-12 ml was obtained. Bromine distilled in the first stages was reduced by

passing sulfur dioxide gas through the solution until the bromine color disappeared. The selenium tetrabromide was reduced by addition of 0.1 to 0.25 gram hydroxylamine hydrochloride. Subsequent heating of the solution on a water bath accelerated production of red selenium.

Estimation of concentration was by visual comparison with standardized samples with 3, 7, 10, 15, 25, 35, and 50 ppm concentrations.

Precision is such that 95% or more of the values range plus or minus 15% of the value given in the tables (Table 2 and following). Systematic error, rather than random error, is believed to be generally lower than the true value inasmuch as certain losses of selenium, thought to be small in comparison with amounts obtained, occurred. Incompleteness of oxidation of selenium by bromine, loss of selenium tetrabromide during distillation, and loss of the same during reduction of bromine to bromide are believed to be the principal sources of error. Reduction of excess bromine was carried out in a cold-water bath to minimize escape of the volatile selenium tetrabromide.

Analysis of plant material was performed by overnight decomposition of 10 grams of air dried sample in 15-20 ml of 30% hydrogen peroxide. The mixture was then evaporated to dryness in a water bath and the residue treated in the same manner as shale samples.

SELENIUM AT CANYON GLEN CAMPGROUNDS

Stratigraphic distribution.—In general, but with some notable exceptions, the results of Beath and others concerning the selenium occurrence in the Manning Canyon Formation has been verified. Selenium is present in unusual concentrations (Table 2). However, important differences exist both as to the absolute value of maximum concentrations, and to the stratigraphic distribution of selenium. For instance Beath (Table 1, bed 14) reports 96.3 ppm in a variegated shale 24 feet thick. The present writer obtained 15, 20, and 20 ppm at 7, 6, and 10 feet, respectively, in the same shale (Table 2, beds 32, 33, and 34).

It is possible that the selenium is not evenly distributed along the strata, or that sampling and analytical errors alone or combined with the foregoing, may have caused the disagreement. Values reported in the present study may be too low due to analytical errors, and it may well be that Beath's sampling caused him to report values too high. It is not known precisely how Beath sampled the section, but if samples were taken from near the surface, it is quite possible that local enrichment by accumulation of selenium-rich decayed vegetable matter may have occurred in the upper part of the profile.

Of the 156½ feet of shales measured by the writer, 73 feet, or 43%, contained values in the range 1-9 ppm; 49½ feet, or 32%, contained values in the range 10-19 ppm; 36½ feet, 23%, contained values in the range 20-29 ppm; and 3 feet, 2%, contained values in the range 30-39 ppm.

TABLE 2.

Detailed stratigraphic section of selected portions of the Manning Canyon Shale, Canyon Glen Campgrounds, Provo Canyon, Utah.*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
41	Shale, resembles bed 40	MC-CG 41-0-0 1963	157-182	25	1

TABLE 2 (CONT.)

40	Shale, gray, calcareous, soft, but not crumbly. Slope former. *Stanleya sp.*	MC-CG 40-0-0 1963	154-157	3	1
39	Limestone, blue gray, slabby, weathers gray, ledge former		151-154	3	Not sampled
38	Shale, gray, medium hardness, fissile, ragged outcrops	MC-CG 38-0-0 1963	142-151	9	1
37	Limestone, shaly, black gray, weathers light brown gray, shaly partings, ragged outcrops.	MC-CG 37-0-0 1963	136-142	6	Not analyzed
36	Shale, gray, soft, crumbly, slope former. *Stanleya* sp., *Aster glaucus.*	MC-CG 36-0-0 1963	132-136	4	10
35	Limestone, shaly, some interbedded shale, blue gray, slope former. *Aster glaucus.*		125-132	7	Not sampled
34	Shale, brownish black, soft, crumbly; gypsum present in 1/16 inch criss-crossing veinlets; calcareous, slope former.	MC-CG 34-0-0 1963	115-125	10	20
33	Shale, black with numerous ferruginous layers, soft, crumbly, slope former, *Stanleya* sp., *Aster glaucus;* calcareous, gypsiferous.	MC-CG 33-0-0 1963	109-115	6	20
32	Shale, brownish gray, soft, crumbly, slope former, *Stanleya* sp. and *Aster glaucus,* calcareous, gypsiferous.	MC-CG 32-0-0 1963	102-109	7	15
31	Limestone, shaly, brown, jagged ledge former	MC-CG 31-0-0 1963	92-102	10	5
30	Shale, brownish black, soft, crumbly, calcareous, slope former. *Stanleya* sp.	MC-CG 30-0-0 1963	91-92	1	15
29	Limestone, shaly to 3 inch beds, brownish black, ledge former		73-91	18	Not sampled
28	Shale, black, resembles bed 26. *Stanley* sp.	MC-CG 28-0-0 1963	68-73	5	20
27	Limestone, blue gray, slabby, ledge former		66-68	2	Not sampled
26	Shale, black, soft, crumbly, contemporary plant roots throughout, slope former	MC-CG 26-0-0 1963	55-66	11	20
25	Limestone, blue black, slabs 1 inch to 6 inches thick, ledge former		49-55	6	Not sampled
24	Shale, gray black, soft, crumbly, slope former	MC-CG 24-0-0 1963	44-49	5	15
23	Limestone, black, shaly on bottom to dense, very fine-grained on top, resembles coal from a distance, ledge former		39-44	5	Not sampled
22	Limestone, blue gray, 3 inch bedding, weathers gray, ledge former		37-39	2	Not sampled

TABLE 2 (CONT.)

21	Shale, resembles bed 19	MC-CG 21-0-0 1963	36-37	1	30
20	Shale, black, gypsiferous, calcareous, traces of limonite on bedding planes Soft, crumbly. Slope former. *Astragalus* sp. (?)	MC-CG 20-0-0 1963	36-37	1	30
19	Shale, mouse gray, brown tint, soft, crumbly, slope former	MC-CG 19-0-0 1963	34½-35	½	20
18	Shale, black, numerous contemporary plant rootlets, soft, crumbly, white efflorescence.	MC-CG 18-0-0 1963	33½-34½	1	30
17	Limestone, blue gray, slabby, ledge former		32-33½	1½	Not sampled
16	Shale, mouse gray, brown tint, resembles bed 13	MC-CG 16-0-0 1963	23-32	9	10
15	Shale, black, limonitic, soft, crumbly, slope former.	MC-CG 15-0-0 1963	19-23	4	20
14	Shale, black, chippy, soft, siliceous-calcareous concretions with disseminated pyrite, slope former.	MC-CG 14-0-0 1963	14-19	5	15
13	Shale, mouse gray, brown tint, soft, crumbly, slope former.	MC-CG 13-0-0 1963	0-14	14	7

Base of the above portion of the section was taken at the lowermost exposure of shale in the bottom of the largest ravine north of the railroad track crossing Provo River at the campgrounds.

Strike of beds: N 70° W; dip, 30° north.

A fault whose relative movement is not observable interrupts the section.

12	Limestone, blue gray, massive, ledge former		84-96	12	Not sampled
11	Shale, chocolate color, ferruginous near top and bottom, soft, crumbly, slope former. *Stanleya* sp.	MC-CG 11-0-0 1963	81½-84	2½	5
10	Limestone. Resembles 8		80-81½	1½	Not sampled
9	Shale, resembles bed 7 *Stanleya* sp.	MC-CG 9-0-0 1963	78-80	2	5
8	Limestone, dark gray,. ferruginous seams, massive, ledge former.		76½-78	1½	Not sampled
7	Shale, black with red and yellow mottling, stringers of gypsum, soft, crumbly, slope former.	MC-CG 7-0-0 1963	75-76½	1½	10
6	Limestone, blue-gray, massive, ledge former.		69-75	6	Not sampled
5	Shale, black with yellow brown to red brown veinlets, soft, crumbly, calcareous, slope former. *Stanleya* sp.	MC-CG 5-0-0 1963	67-69	2	10
4	Sandstone, red-brown to buff, coarse grained to gritty, weathers reddish brown, ledge former.	MC-CG 4-0-0 1963	52-67	15	Not sampled

TABLE 2 (CONT.)

3	Shale, black, crumbly, upper three feet lighter in color, calcareous, slope former. *Stanleya* sp.	MC-CG 3-0-0 1963	37-52	15	10 (?)
2	Limestone, blue gray, massive, cliff former.		12-37	25	Not sampled
1	Shale, brown, bedding ½ inch grading to 2 inches at top; calcareous, weathers brown, slope former.	MC-CG 1-0-0 1963	0-12	12	5

*Begin section at base of 12 foot shale bed exposed in railroad cut about 100 feet west of railroad bridge crossing Provo River. NW ¼, Sec. 4, T. 6 S., R. 3 E.
Strike: N 70° W; dip, 25° North.
Fifty feet of section underlying the massive limestone ledge cropping out above the flume is not described or sampled. The beds above and below carry only small amounts of selenium, and in the limited time available, this lower section, consisting mostly of shales and shaly limestones, was not sampled or described.

Maximum values obtained by the writer were associated with carbonaceous, black, gypsiferous, often limonitic or hematitic, shales (Table 2). Samples MC-CG 18-0-0, 19-0-0, 20-0-0, and 21-0-0, yielded 30, 20, 30, and 30 ppm respectively. High values, though not maximum, were obtained from samples MC-CG 14-0-0, 15-0-0, and 16-0-0, of 15, 20, and 10 ppm respectively.

Maximum concentrations of selenium are associated with dark colored, soft friable, gypsiferous, calcareous, and often limonitic or hematitic shales. Usually, but not always, the so called indicator plants, *Stanleya* sp. and *Aster glaucus* are rooted in the strata. *Astragalus* is found only occasionally.

Shales that are hard and chippy bear less selenium; limestones and sandstones are generally impoverished. The more calcareous shales become the less selenium is noted. The more carbonaceous, ferruginous or pyritic, gypsiferous, and friable a sediment becomes the greater will be the concentration of selenium.

Within one of the most seleniferous beds (samples MC-CG 33-0-0, Table 2, and MC-CG 33-0-10, Table 3), the selenium seem to be most highly concentrated in red or yellow lenses, stringers, or more diffuse splotchy areas derived from oxidation of pyrite. A maximum of 40 ppm was found in red, ferruginous shale intermingled with dark, carbonaceous, gypsiferous shale (Table 3). In a limonitic, hematitic veinlet carrying remnants of pyrite, and surrounded by an incrustation of gypsum up to ⅛ inch thick, 35 ppm of selenium was obtained. In an adjoining dark colored carbonaceous shale, free of gypsum and iron oxides, 10 ppm was obtained at a depth of 24 inches (MC-CG 33-0-8, Table 3).

TABLE 3

A profile down the dip of a seleniferous bed, 33, and some further samples from the same bed at Canyon Glen Campgrounds, Provo Canyon.*

Description	*Sample Number*	*Depth from Surface in Inches*	*Thickness In Inches*	*PPM Selenium*
Shale, carbonaceous, stringers of hematite and limonite, soft, crumbly.	MC-CG 33-0-1 1963	0-6	6	20
As above	MC-CG 33-0-2 1963	6-12	6	25

TABLE 3 (CONT.)

As above	MC-CG 33-0-3 1963	12-20	8	20
As above, but a little less friable.	MC-CG 33-0-4	20-28	8	10
As above	MC-CG 33-0-5 1963	28-36	8	10
As above	MC-CG 33-0-6 1963	36-44	8	20
Shale, all carbonaceous, no ferruginous mottling.	MC-CG† 33-0-7 1963	24		10
Shale, ferruginous, red, soft, friable.	MC-CG† 33-0-8 1963	24		40
Limonite-hematite veinlet surrounded by gypsum, 1/16 inch thick in turn surrounded by carbonaceous shale.	MC-CG† 33-0-9 1963			35
Gypsum veinlets in bed 34-0-0. No calcite with sample.	MC-CG†† 33-0-10 1963			20
Siliceous, calcareous, pyritic nodule. Size of grapefruit. Value of selenium concentration is a minimum value.	MC-CG††† 14-0-1 1963			15

*Samples were taken down dip to a depth of 44 inches to determine the variation of selenium concentration as a function of depth on a given bed. The stratum chosen was midway in bed 33-0-0, and is a six inch layer of black shale mottled with iron oxide stains. The shale is soft and friable and becomes more compact with depth. Samples were taken on 6 to 8 inch intervals.

†Selected samples from the same bed along the outcrop band.

††From bed MC-CG 33-0-0:

†††From bed MC-CG 14-0-0:

This association of organic matter, pyrite, and iron oxide with gypsum suggests that the selenium may have been derived from organic sources. Subsequent reducing conditions during deposition and diagenesis favored accumulation of pyrite in veinlets, and enrichment of selenium in the sulfide phase. Later, oxidation of pyrite may have produced the iron oxides and gypsum. It seems likely then, if the foregoing is true, that selenium is distributed among the organic matter, pyrite, and oxidized products as an oxide, a selenite or a selenate.

It is by no means impossible that selenium was introduced by hydrothermal activity. However, evidence of such activity at Canyon Glen is slight. Widespread development of crosscutting veins, wall rock alteration, and the development of sulfide minerals, other than pyrite, typical of hydrothermal deposits of the region, are not observed. Further study will be necessary to evaluate such effects. At present it seems that hydrothermal effects, if present, are superimposed on the more important deposition and diagenetic processes that concentrated the selenium.

Concentration Versus Depth.—In a sample profile of bed 33-0-0 of the Canyon Glen section, concentration of selenium, as a function of depth, is such

that a maximum value of 25 ppm occurs within the first 12 inches, and decreases to about 10 ppm at about 30 inches, then increases to about 20 ppm at 40 inches (See Table 3). It is believed that the indicator plants draw selenium toward the surface from depths up to 36 inches, the depth of penetration of roots, and causes enrichment in the upper 12 inches of the weathering profile. Weathering of leaves, stems, and fruit of seleniferous vegetation doubtlessly contributes to enrichment near the surface. Concentration at about 18 inches is roughly equal to that at about 36 inches. For that reason, sampling, subsequent to analysis of the depth profile, was made at a depth of about 18 inches in the soft shales.

Indicator Plants.—Aster glaucus (woody aster) collected on bed 33 contained a minimum of 100 ppm (Table 4), and *Stanleya* sp. rooted in the same bed contained a minimum of 50 ppm. Except in localities where downslope movements confuse the stratigraphic profile, these plants are systematically distributed on the seleniferous beds, and in general, the most seleniferous beds produce the greatest density of plant population. This condition is somewhat modified by ecological conditions such as availability of moisture, ability to gain and maintain roots due to steepness of the erosion surface, etc. In general, presence of these plants indicates availability of selenium in the strata in which they are rooted. Lack of the plants usually, but not always, indicates low concentrations of selenium in the strata.

Correlation of indicator plants with seleniferous beds at Canyon Glen is sufficiently positive to suggest that the same relationships might be present at the type locality at Soldier Canyon.

TABLE 4

Analysis of selected plant specimens collected on highly seleniferous beds of the Manning Canyon Shale at Canyon Glen Campgrounds, Provo Canyon, Utah*

MC-CG		PPM Selenium
33-0-10	*Aster glaucus*. Collected from bed 33. Leaves, stems and buds. Strong smell in foliage when prepared for digestion	100
MC-CG 33-0-11	*Stanleya* sp. Collected from beds 32 and 33. Strong, disagreeable odor when vegetation was crushed. Some leaves brown, bloom was gone. Hillside very dry where plants were collected.	50
MC-CG 24-0-1	*Aster glaucus*. Collected from bed 24. Foliage luxuriant. Grew in shady, damp location near the river. Sample included leaves, stem, and flowers.	100
MC-CG 24-0-2	*Oonopsis* (?) sp. Collected from bed 24. Dandelion like plant, but lacks the stems and flowers of dandelion. Resembles *Oonopsis condensatus*, but lacks the flowers shown in the description of that species. Sample was not crackling dry when prepared. Considerable water was present in tissue.	10

*Ten grams of air dried vegetation was ground and digested with 30% hydrogen peroxide by leaving overnight, then evaporating to dryness on a water bath. The material thus derived was treated in the same manner as employed for soils, except that twice the usual amount of bromine was added to assist in oxidation of organic matter during distillation.

SELENIUM AT SOLDIER CANYON

Since the Manning Canyon Shale is more than 1600 feet thick at Soldier Canyon, much too thick to sample in detail for the present study, three detailed

sections were measured and described. The lowermost two are about 20 feet thick, and the uppermost is 75 feet thick. Selection of upper and lower detailed sections was based on occurrence of indicator plants rooted in soft, friable, dark-colored, gypsiferous, sometimes ferruginous shales, i.e., the combination of factors found most favorable to high concentrations of selenium at the Canyon Glen Campgrounds Section.

The middle detailed section is the upper coal cyclothem described by Prince (1963). Samples used for analysis were from Prince's collection on file at Brigham Young University. A principal objective was to determine, if possible, variation of selenium concentration within the cyclothem.

The Lower Section.—Measurement, description, and analysis of the lowermost section is summarized in table 5. Similar to conditions and concentrations at Canyon Glen Campgrounds, a maximum of 30 ppm selenium was found in a dark-colored, mottled red and yellow and gray, soft, friable, gypsiferous shale (Sample MC-SC 47-0-0). Indicator plants were present but not abundant. Specimens of *Stanleya* sp. had been grazed by livestock: flower plumes were removed, and the upper, more tender foliage, was missing.

Indicator plants and dark-colored shales are distributed throughout the lower portion of the formation at Soldier Canyon and suggest a broader distribution of selenium than indicated in table 5.

Bed MC-SC 45-0-0 is a black, soft shale which contains considerable brown calcite with pseudomorphs of limonite after pyrite. The bed, in addition, shows some loss of coherence as though it may have been altered hydrothermally. The sample contains 10 ppm selenium. Comparison with overlying beds (Table 5) indicates that the effect of hydrothermal alteration is to impoverish the rock in selenium. Further study is needed for a more definite evaluation.

TABLE 5

Detailed stratigraphic section of a portion of the Lower Manning Canyon Shale at the type locality, Soldier Canyon, Tooele County, Utah.*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
48	Shale, red, chippy, fissile, slope former.	MC-SC 48-0-0 1963	17-20	3	15
47	Shale, black, variegated with red, yellow, gray, soft, friable, slope former.	MC-SC 47-0-0 1963	13-17	4	30
46	Shale, red brown, soft friable, slope former	MC-SC 46-0-0 1963	9-13	4	15
45	Shale, black, soft, friable, slope former; brown calcite occurs with pseudomorphs of limonite after pyrite; loss of some coherence of the rock.	MC-SC 45-0-0 1963	5-9	4	10
44	Shale, purplish black, calcite stringer, soft, friable, slope former.	MC-SC 44-0-0 1963	0-5	5	10

*The section is in the lowermost part of the type section at Soldier Canyon. Bed 44 overlies Unit 2 of Moyle. (1958). Strike: N. 70°W, dip 45° North. *Stanleya* sp. occurs in this part of the section, but is not as abundant as in other parts of the section. NE ¼ Sec. 33, T. 4 S., R. 4 W.

Selenium in the Coal Cyclothem. Investigation of selenium in the coal cyclothems described and studied by Prince (1963) was not very successful. In spite of the presence of indicator plants, concentrations of selenium throughout the cyclothem proved to be low, i.e., 10 ppm or less (Table 6). Most of the concentrations appeared to be less than 5 ppm, and at these levels the method of analysis employed is not sufficiently definitive. It was hoped that greater concentrations of selenium would be present than were actually found, and that the differences from one part of the cyclothem to another would be more marked. A cyclic repetition of the selenium was not established.

TABLE 6

Detailed stratigraphic section of a middle portion of the Manning Canyon Shale, Soldier Canyon, Utah. (Prince, 1963)*

Unit No.	*Description*	*Thickness Inches*	*Feet Above Base*	*PPM Selenium*
154	Quartzite, medium to light gray. Marks the base of the upper partial cyclothem.	12	190.3	Not sampled
153	Siltstone, brown, shaly, and nodular.	2	189.3	Not sampled
152	Shale, black, dense, noncalcareous.	10	189.2	10
151	Clay, medium gray to light green, waxy.	1	188.3	5
150	Shale, medium gray to light green, noncalcareous.	2	188.2	5
149	Siltstone, brown, slightly calcareous, thin 1" beds, hard and compact.	6	188.1	2
148	Shale, nodular, green to brown, slightly calcareous. ¼ to ½ inch beds.	18	187.6	5
147	Shale, medium gray to dark green, noncalcareous.	12	186.1	1
146	Shale, light green, weathers brown, calcareous, papery to ¼ inch beds, somewhat nodular	9	185.1	8
145	Shale, medium gray to green, slightly calcareous.	28	184.3	3
144	Siltstone, medium gray, weathers light gray, nodular.	3	182.0	No sample
143	Shale, black, noncalcareous, paper thin to ¼ inch beds.	30	181.8	5
142	Shale, black, weathers gray, waxy, noncalcareous, chippy, hard.	6	179.3	3
141	Shale, black, weathers gray, waxy, clayey, very thin beds.	9	178.6	No sample
140	Shale, medium gray to gray, weathers light gray, nodular, noncalcareous.	14	178.0	5
139	Shale, black, dense, silty, somewhat nodular, noncalcareous, ½ inch beds.	7	176.8	10
138	Shale, light gray to medium gray, weathers same with orange mottling, bedding very thin to paper thin.	8	176.3	5
137	Limestone, black, dense, laterally persistent. Key bed for upper cyclothem. Ostracods, pelecypods, low-spired gastropods, brackish marine.	12	175.6	3
136	Shale, roof shale, consists of the following: top 2½ inches, shaly limestone, 3 inches red shale, 2 inches shaly limestone, 3½ inches shale, 2 inches red shale.**	13	174.6	1

TABLE 6 (CONT.)

135	Coal, brown to dark brown lignite, banded, associated with gypsum, and limonitic on weathered surface.	4	173.5	15 (?) Value represents a minimum value.
134	Underclay, black to dark gray, irregular to no bedding, very waxy and carbonaceous.	6	173.2	1
133	Shale, dark gray, silty to sandy, noncalcareous.	2	172.7	1
132	Sandstone, light gray, medium to fine-grained, noncalcareous.	6	172.5	Not sampled
131	Quartzite, light gray to buff, fine to medium grained, orange limonite mottling, thin bedded, crossbedded in part. This and underlying quartzite beds marks the base of the upper complete cyclothem.	33	172.0	Not sampled

*This section is from the upper coal cyclothem in the middle part of the Manning Canyon Shale. Measurements are to the base of the "medial limestone" member, which is approximately 460 feet above the base of the formation. The descriptions given are modified from those given by Prince (1963). SE ¼, NE ¼, Sec. 33, T. 4 S., R. 4 W.
**Sample of shaly limestone only.

The Upper Section.—Indicator plants, *Stanleya* sp., rooted in soft, black, gypsiferous, and sometimes ferruginous shales led the writer to investigate a part of the upper Manning Canyon Shale at Soldier Canyon. (Table 7).

The section consists of 58 feet of shale and 17 feet of limestone. The weighted mean concentration of selenium in the shales is 13 ppm. (Sum of products of thickness times concentration, and the sum divided by the total thickness.) The high value is 45 ppm, associated with bed 41, Table 7; a brownish black, soft, limonitic, gypsiferous shale 1 foot thick. Two other beds are noteworthy for concentration of selenium. Beds 36 and 35 of Table 7, 2 feet and 8 feet thick, have 30 ppm and 25 ppm selenium, respectively. These shales are also brownish black, soft, friable, gypsiferous. *Stanleya* sp. is rooted into each bed.

The presence of indicator plants, such as *Stanleya* sp., and other dark colored, soft shales in the upper part of the Manning Canyon Shale suggest that selenium is more widespread than indicated by the limited measured section. Values shown in table 7 suggest that the upper part of the Manning Canyon Shale is the most seleniferous part of the formation. At Canyon Glen, 156½ feet of shale averages 10.5 ppm; at Soldier Canyon, the section in table 7 averages 13.1 ppm in a 58 foot section. Maximum concentrations of selenium, up to 100 times normal abundance of the element in shale, is associated with soft, black to brownish black, gypsiferous calcareous, often limonitic or hematitic shale.

TABLE 7

Detailed stratigraphic section of an upper portion of the Manning Canyon Shale at the type locality, Soldier Canyon, Tooele County, Utah.*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
42	Limestone, blue gray, thin bedded, shaly, ledge former.		70-75	5	Not sampled
41	Shale, black brown, fissile, soft, limonitic, gypsiferous, calcareous.	MC-SC 41-0-0 1963	29-70	1	45

TABLE 7 (CONT.)

40	Shale, brownish gray, somewhat hard, fissile, bedding up to ¼ inch.	MC-SC 40-0-0 1963	66½-69	2½	20
39	Shale, gray brown, hard. Limonitic and gypsiferous. *Stanleya* sp. rooted in bed nearby.	MC-SC 39-0-0 1963	65-66½	1½	20
38	Limestone, shaly, blue gray, bedding ¼ inch to 6 inches, jagged ledge former.		53-65	12	Not sampled
37	Shale, resembles 36, but not as black or as gypsiferous.	MC-SC 37-0-0 1963	50-53	3	5
36	Shale, brownish black, soft, bedding ⅛ to ¼ inch. Gypsiferous Not limonitic. Two *Stanleya* sp. rooted in bed.	MC-SC 36-0-0 1963	48-50	2	30
35	Shale, gray brown, soft. *Stanleya* sp.	MC-SC 35-0-0 1963	40-48	8	25
34	Shale, gray, fissile, slope former.	MC-SC 34-0-0 1963	20-40	20	10
33	Shale, gray brown, soft, friable, gypsiferous, limonitic in part.	MC-SC 33-0-0 1963	16-20	4	10
32	Shale, gray, fissile, chippy, slope former.	MC-SC 32-0-0 1963	8-16	8	8
31	Shale, black, papery thin, limonitic stains.	MC-SC 31-0-0 1963	4-8	4	7
30	Shale, medium gray, soft, friable, slope former.	MC-SC 30-0-0 1963	2-4	2	5
29	Shale, black, fissile, hard. No hematite or limonite or gypsum. Slope former.	MC-SC 29-0-0 1963	1-2	1	5
28	Shale, black mottled with yellow and orange, fissile, slope former. *Stanleya* sp. rooted in bed.	MC-SC 28-0-0 1963	0-1	1	10
27	Limestone, blue gray, shaly, thin bedded, jagged ledge former.		0 to minus 10		Not sampled

*This section lies approximately 1200 feet above the base of the formation, and is roughly equivalent to unit 26 of Moyle (1958). The analyzed section is two spurs (200 yards) east of Moyle's section. The formation is thinner on the spur where Moyle measured his section than it is at the present locality because of structural complications in his section. NE ¼ Sec. 33, T. 4 S., R. 4 W.

SELENIUM AT LAKE MOUNTAIN

Lake Mountain is 20 miles south of Soldier Canyon, and 20 miles due west of Provo Canyon (Text-fig. 1). Indicator plants are wholly lacking in the sections visited by the writer on Lake Mountain. The author walked over most of the section described by Moyle (1958) and Tidwell (1962), and not a single indicator plant was found. Either other ecological conditions make the growth of such plants unfavorable or the selenium content of the formation is too low to support such a flora. Perhaps indicator plants find the concen-

tration of the selenium from 1 to 10 ppm too low to meet requirements for growth.

Data summarized in table 8 show that the concentration of selenium in the stratigraphic vicinity of the early Pennsylvanian flora described by Tidwell (1962) is very low. The highest value, associated with bed 4 of Table 8 is 7 ppm. In general the concentration is near 1 ppm, the least concentrations of selenium of the five sections studied.

It is thought by Tidwell (personal communication) and by Moyle (1958) that the Lake Mountain section represents terrestrial deposition to a greater degree than the other sections. Sandstones are more abundant at Lake Mountain, and so are fossil terrestrial plants.

It is possible that terrestrial conditions are less favorable to concentration of selenium than brackish or marine conditions. Since the brackish to marine rocks of the upper part of the Manning Canyon Shale at Soldier Canyon are the most seleniferous section yet encountered, and since equivalent rocks at Lake Mountain seem to be more terrestrial and are least seleniferous, it is suggested that concentration of selenium is somehow related to brackish water or marine conditions.

TABLE 8

Section across plant-bearing strata in the Manning Canyon Shale, Jackrabbit Quarry, Lake Mountain, Utah (Tidwell, 1962).*

Bed No.	*Description*	*Sample Number*	*Feet Above Base*	*Thickness in feet*	*PPM Selenium*
12	Shale, pinkish brown, weathered, approaches surface on shallow side of quarry on the east.		71-73	2	Not sampled
11	Shale, pinkish brown, fissile, laminated.	MC-LM 11-0-0 1963	66-71	5	1
10	Shale, resembles 11	MC-LM 10-0-0 1963	60-66	6	1
9	Shale, resembles 11	MC-LM 9-0-0 1963	53-60	7	1
8	Shale, pinkish brown, laminated, weathers in slabs. Plants found by Tidwell in this bed and in 7.	MC-LM 8-0-0 1963	46-53	7	1
7	Shale, pink, laminated, weathers in slabs ¼ inch to 6 inches, some unidentifiable plant remains. Lower part of most productive fossil plant beds.	MC-LM 7-0-0 1963	41-46	5	1
6	Shale, brownish pink, variegated, crumbly. Limonitic stains.	MC-LM 6-0-0 1963	37-41	4	2
5	Shale, brown gray, limonitic on surface, crumbly.	MC-LM 5-0-0 1963	30-37	7	5
4	Shale, gray, some limonite, but not as much as in 3-0-0. Crumbly.	MC-LM 4-0-0 1963	22-30	8	7
3	Shale, gray with yellow iron oxide stain abundant, crumbly.	MC-LM 3-0-0 1963	13-22	9	3

TABLE 8 (CONT.)

2	Shale, yellowish gray, beds crumpled by folding, part of bed cut out by folding; dip changes to east.	MC-LM 2-0-0 1963	6-13	7	1
1	Shale, variegated with brown, gray, and yellow, bed is crumpled by folding.	MC-LM 1-0-0 1963	0-6	6	3

*Section begins on top of blue-gray limestone which weathers pink on the west side of the quarry. The dip of the bed is nearly vertical, and the strike is about N 2° E. Beds 7 and 8 correlate with those beds which have yielded numerous *Alethopteris, Neuropteris,* and *Calamites* (Tidwell, 1962). SW ¼, SW ¼ Sec. 7, T. 7 S., R. 1 E.

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Some Monoclinic Amphiboles and Relation of Their Physical Properties to Chemical Composition and Crystal Structure*

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ABSTRACT.—The amphibole mineral group has been difficult to classify due to complexities introduced by the large number of ions that can substitute, either partially or completely, in the five structural sites. Each site has definite size, valence, and coordination number requirements. By assigning a code number to each possible ion in each possible site, every possible combination of ion and position can be used to give a unique classification scheme relating structural position to chemical composition. A species of hornblende chosen from Dana's System of Mineralogy (1892) is used to illustrate this classification system.

Ten amphibole minerals obtained from supply houses were chemically analysed and physical properties—i.e. index of refraction, 2V angle, C∧Z, pleochroism, DTA, and X-ray — were observed to determine if the classification system would be applicable and to try correlation of chemical composition and physical properties. Fe^{2+} And Fe^{3+} give the mineral a higher refractive index, a smaller 2V angle, darker pleochroic colors and a more nearly black color in hand samples. Presence of fluoride ions, as seen in sample 6, seems to increase the C∧Z. Neither the number of Si^{4+} replaced in the tetrahedral sites nor the number of alkali ions present in position "A" show any observable effect upon optical properties. An expected cell size increase with increasing substitution of Al^{3+} for Si^{4+} in tetrahedral sites was not observed in X-ray patterns; however, there is a decrease in cell size with an increase of trivalent ions in octahedral sites. A decrease of Ca^{2+} in cubic sites also tends to indicate a decrease in cell size. DTA shows that oxidation and hyrdation take place gradually all along the heating curve. Structure does not break down even at temperatures of 1100°C. A decrease in Ca^{2+} and an increase in Na^{+} and K^{+} lowers the temperature at which the endothermic reaction takes place.

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ILLUSTRATIONS

*A thesis submitted to the Faculty of the Department of Geology, Brigham Young University in partial fulfillment of the requirements for the degree Master of Science.

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INTRODUCTION

Combined amphibole and pyroxene mineral groups make up about 17%, by weight, of the earth's crust and are second only to feldspars in abundance. Amphibole minerals occur in many types of rocks. Hornblende species, for example, occur in great abundance in intermediate igneous rocks, in metamorphic schists and gneisses, and as a detrital mineral in some sedimentary rocks. Some amphibole variety forms in nearly all igneous rocks, in many metamorphic rocks and even as alteration products of other ferro-magnesium minerals.

Classification of the amphibole group is poorly organized and confused by indefinite mineral species. Wahlstrom (1947) commented that the nomenclature of the amphiboles is one of convenience and is not completely established. Kerr (1959) noted that the amphibole group is one of the most complex of all mineral groups, and many amphibole minerals cannot be placed within his list of species.

Amphibole minerals are hydrous silicates containing some combination of aluminum, magnesium, calcium, ferric iron, ferrous iron, sodium, and many other elements in minor amounts through ionic substitution. Amphiboles have a double chain crystal structure which gives them a bladed form and 56°, 124° cleavage angles. Within this structural framework are five different coordination positions to be occupied by 20 different ions. Complexity of the amphiboles is caused by random substitution of ions in similar coordination positions, and even some substitution in dissimilar positions by the same ions. For example, aluminum ions may substitute for silicon ions in tetrahedral coordination and may also substitute for magnesium ions in octahedral coordination.

The amphibole structure was first worked out by Warren (1929) using tremolite. In general the structural framework is formed by four oxygen ions arranged around one silicon ion in tetrahedral coordination. Silica tetrahedra share oxygen ions, alternating two and three per tetrahedra, forming double chains of infinite length parallel to the c-axis. The distance from one oxygen link to the next determines the "c" unit cell dimension. Groups of double chains are held together by various cations between the double chains in holes or "sites" of six fold and eight fold coordination formed by the oxygen framework. The problem of nomenclature, therefore, is one of relating structural sites to the occupying elements, and to the amount of substitution permitted.

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HISTORY OF AMPHIBOLE NOMENCLATURE

The term "amphibole" first appeared in literature in 1801 when Haüy used it to denote a mineral group containing hornblende, actinolite, and tremolite. A large number of other poorly defined species have been included in the amphibole group since that time.

Tschermak (1864) was one of the earliest workers to investigate the silicate structures. He introduced the concept of solid solution in minerals, especially in the plagioclase feldspars and other silicate structures. From a consideration of mineral chemistry he was able to give the ionic requirements for isomorphous compounds. Tschermak discovered that an increase in the iron content was observable in forms with a higher index of refraction, an observation many other researchers have noted since his time.

Allen and Clement (1908) experimented with the effect of heat on tremolite. When heated to 900°C. and held at this temperature for a period of time, tremolite lost most of its water, but, the mineral still retained its homogeneity and no sudden property changes took place. They thought that perhaps the water was dissolved water and tremolite was a solid solution phase. Later work showed that water was chemically combined and not a separate phase.

Ford (1914) made a detailed study of optical properties of amphiboles and concluded that the mean index of refraction was the best indicator of the chemical composition and therefore of the mineral species. He noticed that silicon, calcium, and magnsium ions had little effect on the refractive index.

Clarke (1914) proposed the concept of silicic acids to help explain composition of the various silicates, including the amphibole group. Acidic, basic and normal salts were introduced, and elaborate structural formulae were derived. Later work proved these hypothetical silicic acids could not be synthesized, nor could they be found in solutions of the minerals themselves. Berry and Mason (1959) state that X-ray investigations provided the means to disprove the silicic acid theory and made possible a classification based on structure.

Schaller (1916), from chemical considerations, worked out the correct formula for tremolite. He expressed it, in oxides of the elements, as 2CaO-

$5MgO\text{-}8SiO_2\text{-}H_2O$. Schaller suggested that the water probably occured as OH ions and was a definite part of the structure, and not dissolved water in tremolite.

Kuntz (1930) derived the correct formulae for actinolite, kupfferite and grunerite, analysed numerous amphibole minerals, measured their optical properties, and correlated this information by means of a series of graphs.

Position of each atom in the amphibole structure was worked out by Warren (1929) for tremolite by X-ray rotation photographs. Warren showed how the tremolite structure could be derived from diopside, a pyrozene variety, that tremolite, hornblende, grunerite, and kupfferite all had the same structure but with slightly different measurements, and that these differences were due to replacement by different elements.

Bragg (1930) and his students investigated many other silicate minerals by X-ray diffraction. Their work suggested a classification of silicates based upon the number, arrangement, and number of shared oxygen atoms (or corners) of silica tetrahedra in the structure. This sheme is the basis of present day silicate nomenclature.

Berman (1937) divided monoclinic amphiboles, on a structural and chemical basis, into three series; the cummingtonite series with the form $X_7Z_8O_{22}(OH)_2$, the tremolite-actinolite series with the form $W_2X_5Z_8O_{22}(OH)_2$, and the hornblende series with form $W_3(XY)_5Z_8O_{22}(OH,F)_2$. In each case W may equal Ca, Na, Li, and K. X may equal Mg, Fe^{2+}, Mn^{2+}. Y may equal Al, Fe^{3+}, and Ti^{4+}. Z equals Al and Si in tetrahedral coordination. Berman further subdivides the hornblende series into four species (Table 1).

TABLE 1
Hornblende species of Berman (1937)

Species	*Si:Al*	*X*	*Y*
hornblende-edenite	7:1	5	0
hastingsite	6:2	4	1
glaucophane	8:0	3	2
arfvedsonite	8:0	4	1

It should be noted that Berman separated the ions in the octahedral sites into their bivalent and trivalent components.

Hallimond (1943) recognized the importance of aluminum ions replacing silicon ions in tetrahedral sites and the introduction of alkali ions into a position that is usually vacant in the cummingtonite and tremolite-actinolite series. Hallimond observed that the number of silicon ions rarely drops below six, *i.e.* two Si^{4+} out of eight replaced by 2 Al^{3+} ions per one-half unit cell of 24 anions, and that calcium ions rarely rise above two ions per one-half unit cell. Hence, by starting with the simple tremolite formula, $Ca_2Mg_5Si_8O_{22}(OH)_2$, and using two types of substitutions ($2Na^+$ and $2Al^{3+}$ for $2Si^{4+}$, and $4Al^{3+}$ for $2Si^{4+}$ and $2Mg^{2+}$) he could graphically reproduce most of the common hornblende species on a partial triangular diagram. Winchell (1945) noted that the former substitution ($2Na^+$ and $2Al^{3+}$ for $2Si^{4+}$) was inconsistant with the amphibole structure, *i.e.* too much Na for the position available, but, that it could be replaced by two other substitutions as follows; Na^+ and Al^{3+} for Si^{4+}, and $2Al^{3+}$ for Mg^{2+} and Si^{4+}.

Although he stated that the composition of hornblende varies in so many ways that no ordinary diagram can be used to represent these variations, Winchell (1931, 1945) still attempted to correlate changes in chemical composition with measured physical properties of the mineral, generally on two dimensional diagrams. Hence, he was limited to the consideration of only two variables, or two combinations of variables, at one time. Winchell diagramed the change in molecular percentage of end members versus various optical properties. He used Hallimond's partial triangle as a base and added a vertical coordinate to show, in addition to the variations in Hallimond's variables, the effects of decreasing the number of Al^{3+} ions in tetrahedral coordination and the substitution of Fe^{2+} for Mg^{2+} ions on the optical properties of hornblende. Sundius (1946) questioned the usefulness and accuracy of this diagram and Rabbitt (1948) suggested that showing changes in molecular percentage of end members is not appropriate because end members are seldom found in nature and mixing on a molecular basis doesn't occur.

Sundius (1946) stated the literature complicates and confuses the relationships in the hornblende group and that from a consideration of structural requirements, plus results of many chemical analyses, all hornblende species found in nature can be derived from the tremolite formula by a very small number of substitutions. The chief "type forming" kinds of substitutions he found were; (1) introduction of alkali ions plus the various methods by which the alkali ions substitute for other ions, usually Ca, and, (2) exchange of Si^{4+} and Mg^{2+} for $2Al^{3+}$. If a substitution is carried out to completion Sundius calls the new formula an "end member" formula. If a substitution proceeds only part way in nature, although theoretically it could proceed further, Sundius calls the formula a "standard type" formula. Sundius (1946) classified the hornblendes by means of these substitutions (Text-fig.1).

Since Mg^{2+} and Fe^{2+} are almost completely exchangeable, both formulae names are given. All other hornblendes can be derived from these standard formulae by various substitutions. Sundius noted the introduction of Al^{3+} ions into the tetrahedral site tends to increase the refractive index and decrease the 2V angle of the mineral.

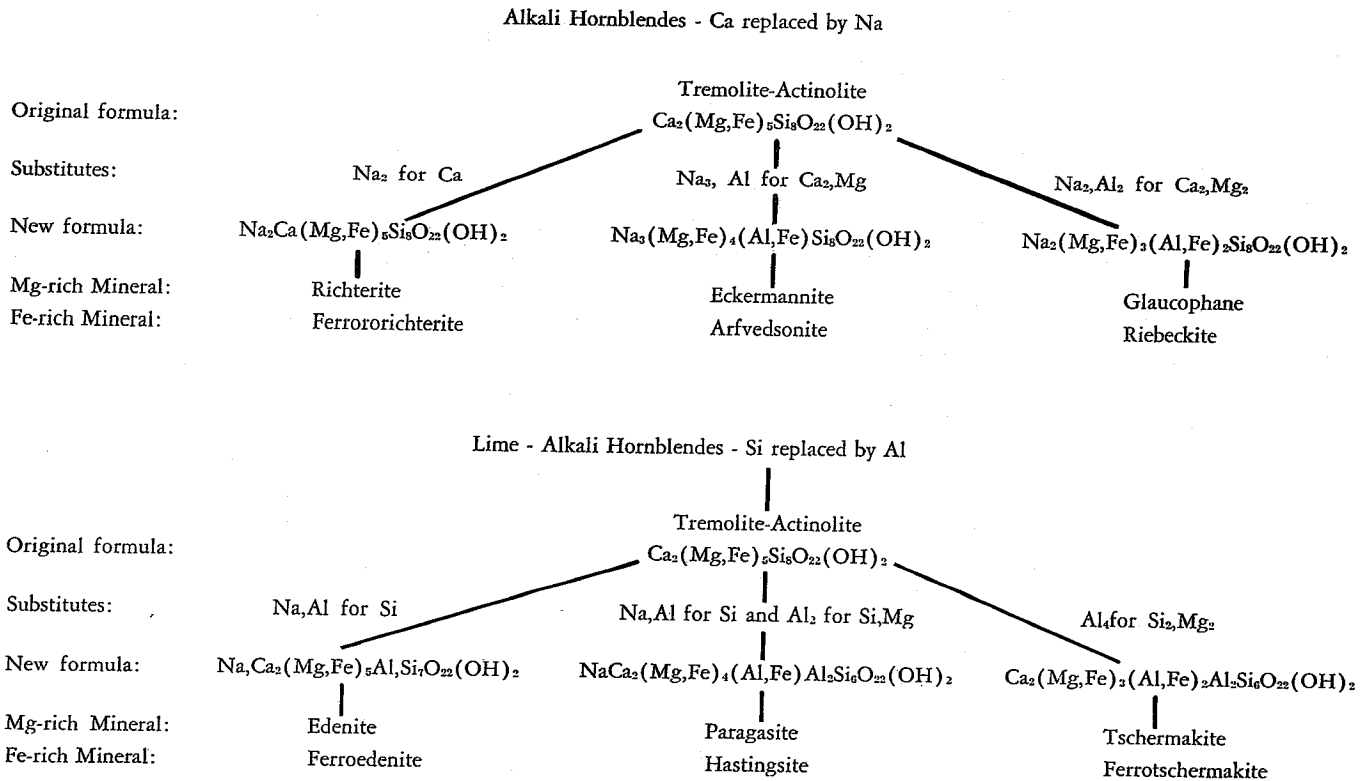
However complete this hornblende classification seems to be, it should be noted that minor elements, such as manganese, titanium, and fluorine, are not considered and these ions sometimes greatly influenced changes in physical properties. Also, as has been suggested, not only the ions involved but even their position in the structure affects physical properties of a mineral. Thus if it is known which elements occupy all possible structural sites, the amphibole species can be completely described.

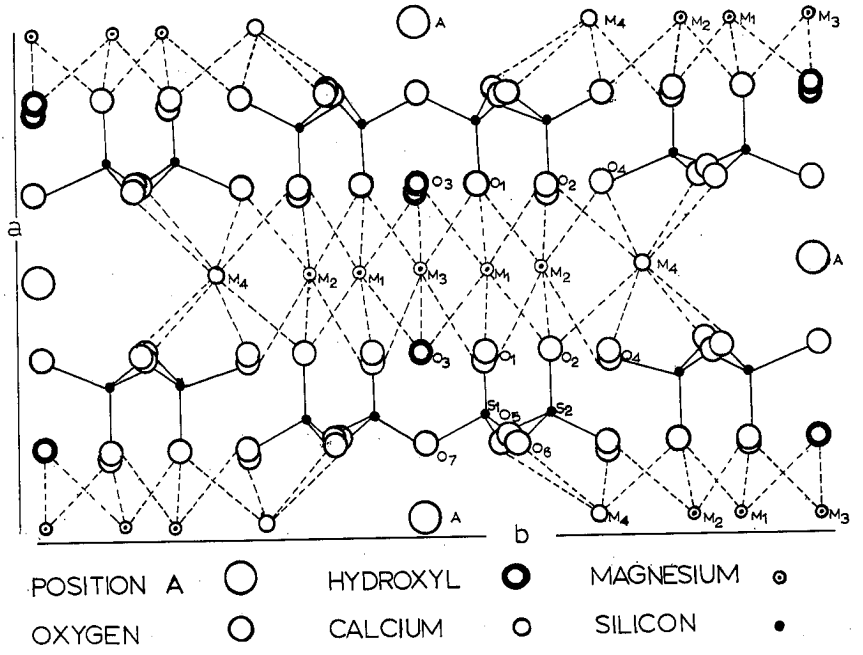
AMPHIBOLE STRUCTURE

Amphibole structure as determined by Warren (1930) is reproduced in text-figure 2 for reference purposes. The following discussion pertains to this diagram. Some oxygen ions should be superimposed but have been offset to indicate the third dimension. The view is perpendicular to the 001 plane, *i.e.* parallel to the c-axis.

There are 48 anions in the unit cell, however, one-half of the cell is the mirror image of the other half, thus, a working unit of 24 anions is convenient. In a one-half unit cell of 24 anions, 22 of these anions are normally oxygen ions surrounding the silicon ions in a tetrahedral arrangement. These

TEXT-FIGURE 1. —A classification for hornblendes as proposed by Sundius (1946).





TEXT-FIGURE 2. —Structure of monoclinic amphiboles.

oxygen ions form the framework of the amphibole minerals. The other two anions, O_3 in diagram, are normally OH^- ions although F^- or Cl^- ions sometimes substitute. The OH^- ions are bonded only to cations between the chains, not to the tetrahedra.

A one-half unit cell contains eight tetrahedral sites of four fold coordination within the chains, labeled S in figure 2. The four oxygen anions form a cavity that will accommodate a cation of ionic radius 0.316 Å without distortion of the structure, but, may also accept a cation with ionic radius as large as 0.580 Å before the structure will be distorted enough to shift to higher coordination. For a symmetrical distribution of charges throughout the structure, a cation in this position should have a valence of +4 although cations with +3 charge many times substitute in this position.

There are five octahedral sites of six fold coordination between the double chains, labeled $M_{1,2,3}$ in figure 2. The cavity formed by the anions exactly accommodates a cation of ionic radius 0.580 Å but will accept a cation with an ionic radius as large as 1.02 Å. The cation should have a valence of +2 for symmetrical distribution of charges throughout the structure, although cations with +3 charge or +1 charge are often substituted.

There are two cubic sites of eight fold coordination, per 24 anions, located between the chains and noted as M_4 in figure 2. This position requires a cation with a minimum ionic radius of 1.02 Å and a maximum radius of 1.40 Å. A charge of +2 is needed for a symmetrical balance of charges, but, many times cations with a +1 charge fill this position.

There is one position, per 24 anions, labeled A in the diagram, normally unoccupied in the actinolite-tremolite and cummingtonite series, but usually occupied, to some extent, in the hornblende series, that requires a cation with an ionic radius larger than 1.02 Å and a charge of +1.

Factors Influencing Ions and Positions

For purposes of reference during the following discussion a table of the possible cations occuring in amphibole minerals, listing their valence, ionic radius, radius ratio compared with oxygen, and their observed coordination numbers, is given below in table 2. Values were taken from Berry and Mason 1959, the Rankama and Sahama (1950). Stability ranges of the radius ratios for the various coordination numbers are also given. The smaller figure of this range is the size of the cavity with the anions "touching." The larger figure is the maximum size of the cavity with anions "spread apart" by cations. If the anions are separated more, there will be room for another anion to enter the arrangement and thus raise the coordination number. The most stable position is somewhere between the two extremes.

TABLE 2

Ion size and stability range

Ion	*Valence*	*Ionic Radius (Å)*	*Rc:Ra**	*Coordination Number*
Si	4	0.42 Å	0.30	4,
Al	3	0.51	0.36	4,6
Cr	3	0.63	0.45	6
Fe	3	0.64	0.46	6
Mg	2	0.66	0.47	6
Ti	4	0.68	0.49	6
Li	1	0.68	0.49	6
Ni	2	0.69	0.50	6
Mn	3	0.70	0.50	6
Fe	2	0.74	0.53	6
Zn	2	0.74	0.53	6
Mn	2	0.80	0.57	6
Na	1	0.97	0.69	6,8
Ca	2	0.99	0.71	6,8
K	1	1.33	0.95	8,12
Ba	2	1.34	0.96	8,12
O	-2	1.40		
OH	-1	1.40		
F	-1	1.36		
Cl	-1	1.81		

Stability Ranges for Radius Ratios
0.000 - 0.225 for 2-fold coordination
0.225 - 0.414 for 4-fold, tetrahedral coordination
0.414 - 0.732 for 6-fold, octahedral coordination
0.732 - 1.000 for 8-fold, cubic coordination
1.000 and larger for 12-fold coordination

*Ra is the radius of an O_2^- ion.

Many chemical analyses of amphiboles have been published and position in the structure which the various elements occupy has been determined, but, limits for the various substitutions, except for Al and perhaps Si, are not known. Various factors such as the ion's radius, its electronegativity, its co-

ordination number, its valence, and its availability at the time of the mineral's formation will have an effect on the limits of substitution and position occupied.

Tetrahedral Sites

The eight tetradedral sites, in a half unit cell of 24 anions, are all similar and may all be filled by Si^{4+} as in tremolite. Silicon ions fit well in this position and never exceed more than eight ions per half unit cell. It is assumed that all Si^{4+} are in tetrahedral sites because of their small radius and 4+ charge. Furthermore it is assumed that all tetrahedral sites are filled by some ion because the high negative charge would have the strongest attraction of any position in the structure for a cation. An empty position within the chain framework would cause a more unstable structure than an empty position between the chains.

Although the radius of Al^{3+} is larger and its valence smaller than Si^{4+}, it may substitute for Si^{4+} in the hornblende series. Its smaller charge can be balanced either by the introduction of a trivalent ion into the octahedral sites, or the introduction of a monovalent ion into a vacant position A (Text-figure2).

Occasionally there is not enough Si^{4+} plus Al^{3+} present to completely fill the tetrahedral sites and in such instances Fe^{3+} may be present in tetrahedral coordination. Although Fe^{3+} is large the structure seems to permit a certain amount of strain and usually the amount of Fe^{3+} needed to fill the remaining sites is small.

The only variation occurring in the tetrahedral sites is the amount of Si^{4+} replaced. Therefore, a number "Y" shall be used to indicate the number of tetrahedral sites, per 24 anions, not filled by a Si^{4+} ion, or the number filled by Al^{3+}. This notation has been used before in silicate structures, Phillips (1954 *ms.*). Sundius and Hallimond recognized the implications of an Al^{3+} ion replacing Si^{4+} in the amphibole structure. Sundius (1946) set the limit for Y at 2.27 which was the highest amount of Al^{3+} replacing Si^{4+} in hornblende. Hallimond (1943) gives an analysis for basaltic hornblende in which 2.44 Si^{4+} ions have been replaced by Al^{3+} and Fe^{3+}. Thus Y may vary from 0 to at least 2.44 although those greater than 2.00 will not be common.

Octahedral Sites

The five octahedral sites are not all similar but may all be filled by Mg^{2+} as in the case of tremolite. Positions of these octahedral sites in the structure are shown in text-figure 2 as Mg^{2+}. The slight difference in the octahedral sites is due to the fact that M_2 is bonded to six oxygen ions while M_3 and M_1 are bonded to one OH^- and five oxygen ions. Thus the M_2 position has a slightly lower electro-negativity than M_3 and M_1, and because Mg^{2+} has a slightly lower electro-negativity than Fe^{2+}, Mg^{2+} will be favored for this position (Ghose, 1962).

Bivalent ions reported in the octahedral sites are Mg^{2+}, Fe^{2+}, Mn^{2+}, Ni^{2+}, Zn^{2+} and Ca^{2+}. They all fall within the proper range of radius ratios although they occur near the upper limit. Mg^{2+} and Fe^{2+} usually fill this position and are usually considered completely replaceable, but, pure Fe^{2+} end members are seldom found in nature while pure Mg^{2+} end members are common. Tremolite often contains only Mg^{2+} in octahedral sites and actinolite rarely exceeds a ratio of 4 Fe^{2+}: 1 Mg^{2+}. Mn^{2+} is reported in many analyses but usually in small amounts. Zn^{2+} and Ni^{2+} are seldom reported in a chemical analysis of an amphibole. Ca^{2+} usually fills the eight-fold positions but may

substitute in the octahedral site if there is a vacancy and if cubic sites are filled.

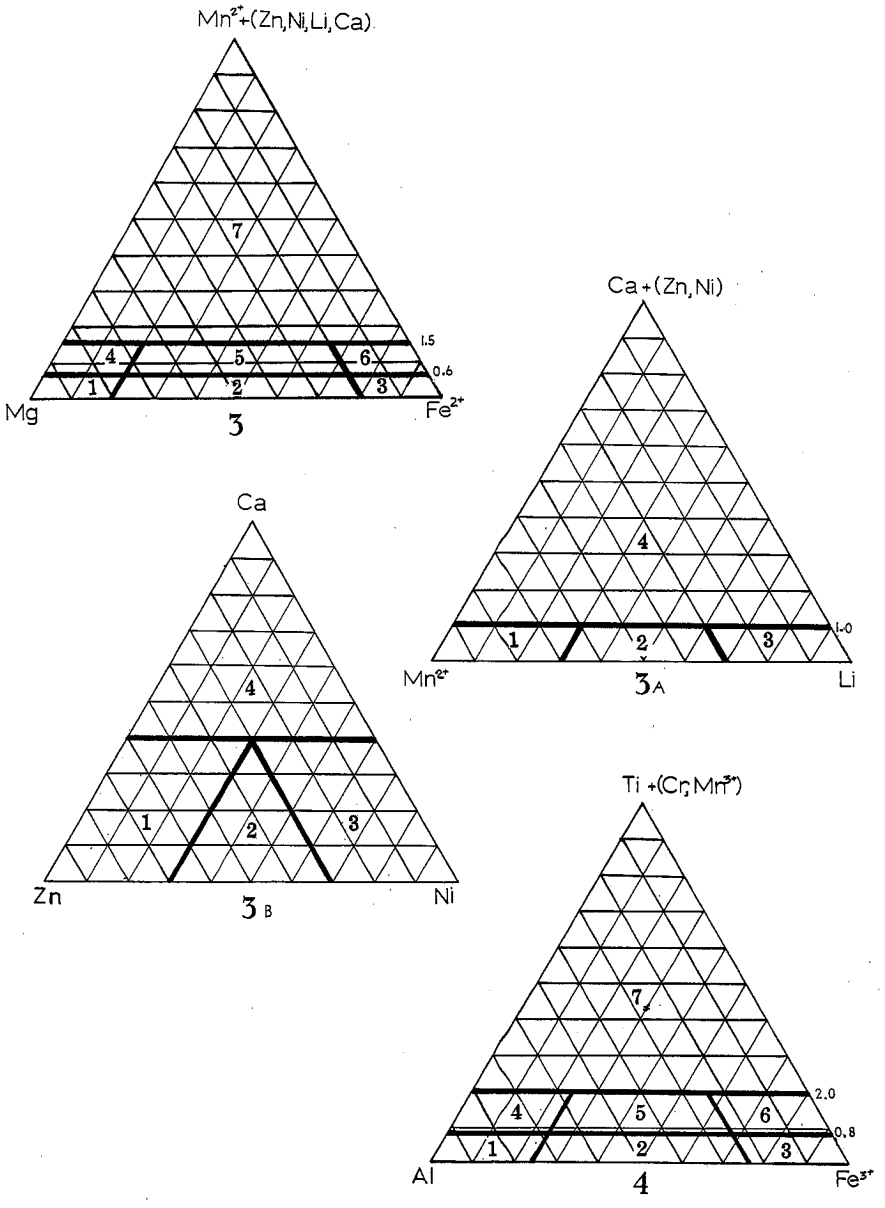
When Y=O the octahedral sites are usually filled by bivalent ions but as Y gets larger trivalent ions are introduced. Trivalent ions reported in octahedral positions are Al^{3+}. Fe^{3+}, Cr^{3+}, Mn^{3+} as are also tetravalent Ti^{4+}, and monovalent Li^{+}. These ions all are in the lower range of radius ratios for octahedral coordination. Al^{3+} and Fe^{3+} are the common trivalent ions found in this position, Ti^{4+} is often reported in small amounts, Cr^{3+} and Mn^{3+} are seldom reported, and Li^{+} is common but only occasionally present in relatively large amounts. Sundius (1946) gives an analysis, with Y=O, in which two trivalent ions in octahedral sites were balanced by $\frac{1}{2}$ ion of Li^{+} in octahedral position plus $1\frac{1}{2}$ ions of Na^{+} in cubic coordination.

Trivalent ions are necessary in the octahedral positions either to balance charges of trivalent ions in tetrahedral positions or monovalent ions in cubic positions. In some analyses more trivalent ions are present in octahedral sites than are needed to balance trivalent ions in tetrahedral sites and monovalent ions in cubic sites. In such cases one octahedral site must be left vacant for every two excess trivalent ions. Chemical analyses usually show an excess of ions available for octahedral sites rather than vacancies. The reason for this condition has not been determined. There actually may be an excess of ions present. Hallimond (1943) notes that an error of only one percent in the calculation of the percentage of H_2O can change the number of cations in the octahedral sites by 0.3 cations. A small change in the percentage of H_2O has a greater effect upon cations in octahedral positions than elsewhere. A chemical analysis with less than two OH^{-} ions usually shows more than five cations in octahedral sites while an analysis with more than two OH^{-} anions usually shows less than five cations in octahedral sites. Most chemical analyses show less than two OH^{-} anions.

The relationship between bivalent ions and trivalent ions in octahedral sites becomes very complex in the hornblende series. Thus, in considering the important variations in the octahedral sites, it is more convenient to consider trivalent and bivalent ions separately. The number "P" will be used to indicate the number of octahedral sites, out of 5 available sites, not filled by bivalent ions *i.e.* the number filled by trivalent ions. From reported chemical analyses of amphiboles it may be observed that P can vary from 0.000 in species such as tremolite, where all octahedral sites are filled with bivalent ions, to 3.45 in gastaldite where 3.45 out of five bivalent ions are replaced by trivalent ions (Sundius, 1946).

Number of bivalent ions in octahedral sites can be recalculated to 100% and position of the relative percentage of any combination of bivalent ions shown as a point on the triangular diagram in text-figure 3. The particular number of the subdivision into which some combination of bivalent ions falls will be called the "R^{2+}" number. If the R^{2+} is seven, Mn^{2+}, Zn^{2+}, Ni^{2+}, Ca^{2+} and Li^{+} are calculated to 100% and referred to the triangular diagram in text-figure 3a, to obtain an "$R^{2+}a$" number. If the $R^{2+}a$ number is four, Ca^{2+}, Zn^{2+} and Ni^{2+} are recalculated to 100% and referred to the triangular diagram in figure 3b for "$R^{2+}b$".

The trivalent ions are treated in a similar manner. Trivalent ions are calculated to 100% and represented as a point on the triangular diagram in



TEXT-FIGURE 3. —Triangular coordinate diagram used to find the "R^{+2}" number by plotting relative percentages of bivalent ions in octahedral coordinate positions.
TEXT-FIGURE 3a.—Triangular coordinate diagram used to find the "$R^{+2}a$" number.
TEXT-FIGURE 3b.—Triangular coordinate diagram used to find the "$R^{+2}b$" number.
TEXT-FIGURE 4. —Triangular coordinate diagram used to find the "R^{+3}" number by plotting relative percentages of trivalent ions in octahedral coordinate positions.

text-figure 4 to obtain an "R^{3+}" number. When no trivalent ions exist in octahedral position, R^{3+} equals zero. To completely define the octahedral position three variables are needed; the "P" number, the "R^{2+}ab" number, and the "R^{3+}" number.

Triangular coordinate diagrams are used so that three variables may be considered simultaneously, and only ions are considered, since the change involved is one of ionic substitution, not changes in end member molecules.

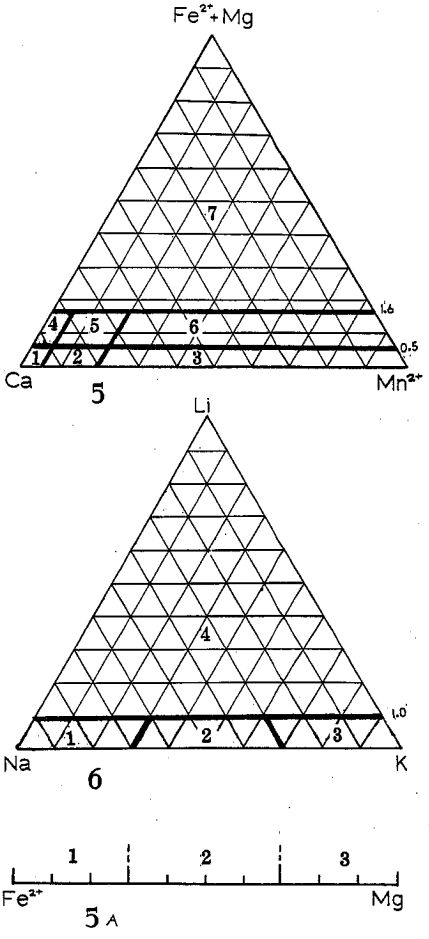
Cubic Sites

Cubic sites may contain the bivalent ions Ca^{2+}, Mn^{2+}, Fe^{2+}, Mg^{2+} and monovalent ions Na^{+}, K^{+} and Li^{+}. Ca^{2+} has an appropriate size and charge for this position and normally occurs here, sometimes completely filling this position in the tremolite-actinolite series. Although in minor amounts, Mn^{2+} usually appears in chemical analyses and may be found in either octahedral or cubic sites. Fe^{2+}, and especially Mg^{2+}, are small for cubic coordination, see table 1. However, in the cummingtonite series Warren (1930) gives a chemical analysis in which Mg^{2+} and Fe^{2+} fills all octahedral sites plus 90% of the cubic sites. Warren (1930) states, "it turns out that the eight oxygen atoms about Ca are so arranged that on replacement of Ca by Mg six of the oxygens can move closer and form a nearly regular octahedron about the Mg atom. Moreover the remaining two oxygens are each bound to two silicons and so have their valence bonds already fully satisfied." The shift effects the structure so little that almost identical X-ray patterns result. Ghose (1962) determined that the M_4 position (cubic site) in cummingtonite has a stronger affinity for Fe^{2+} than Mg^{2+} because of Fe^{2+}'s stronger electronegativity. Ghose also suggests that the M_4-O_4 bond (Text-fig. 2) is covalent. The M_4-O_4 bond is important in amphiboles because it controls the β angle which makes the mineral monoclinic or orthorhombic (Whittaker, 1960).

The monovalent ions Na^{+} and K^{+} also occur in 8-fold coordination and can substitute for Ca^{2+}, if there are excess trivalent ions in octahedral coordination, or excess alkali ions may fill the A position and require substitution of a monovalent ion for Ca^{2+} in cubic coordination to maintain charge balance. Li^{+} is much smaller than K^{+} or Na^{+} and will usually occur in a six-fold coordination like Mg^{2+}.

In considering various ions in cubic sites it is convenient to consider monovalent and bivalent ions separately. "T" will be used to indicate the number of cubic sites not filled by bivalent ions. Tremolite-actinolite have all cubic sites filled by Ca^{2+} and hence T=O. A chemical analysis of eckermannite given by Sundius (1946) has 1.95 ions of Na^{+} replacing Ca^{2+} in 8-fold coordination. Thus T must vary from 0 to at least 1.95.

The bivalent ions are calculated at 100% and plotted on the triangular diagram shown in figure 5. The number representing the relative percentage of bivalent ions will be called the "Q^{2+}" number. If this position falls in subdivision seven, the composition is referred to figure 5a for the "Q^{2+}" number. The same system is used for the monovalent ions and their relative percentage is plotted on the triangular diagram in text-figure 6 to obtain the "Q^{1+}" number. In many analyses there will be no monovalent ions in the 8-fold position in which case Q^{1+} equals zero. Three variables, T, Q^{2+}a, and Q^{1+} are necessary to completely define the cubic position.



TEXT-FIGURE 5. —Triangular coordinate diagram used to find the "Q^{+2}" number by plotting the relative percentages of bivalent ions in the cubic coordination position.
TEXT-FIGURE 5a.—Diagram used to find the "$Q^{+2}a$" number.
TEXT-FIGURE 6. —Triangular coordinate diagram used to find the "Q^{+1}" number by plotting the relative percentages of monovalent ions in the cubic coordinate position.

Position A*

Another possible position for an ion is the position at A (Text-fig. 2) which is usually vacant in the cummingtonite and tremolite-actinolite series but occupied in the hornblende series by Na^+, K^+, Ca^{2+} and sometimes Ba^{2+}. Warren (1930) stated, concerning position A,

> "in this position a small atom such as Mg^{2+} would have only two oxygen neighbors and these two oxygens are already bound to two silicons each and have their electrostatic valence bonds already satisfied. The position of AA' (position A in figure 2 of present paper) was

*As used by Bragg (1930) and Warren (1930).

therefore considered to be highly improbable for a small atom such as Mg^{2+}—A larger atom such as Na^+ if situated at position AA' would have six oxygen neighbors—in normal amphiboles each of the six oxygens has its electrostatic valence bonds fully satisfied—in hornblendes with high aluminum content, where a large fraction of Si in the chains is replaced by Al this is no longer the case. In these circumstances the position AA' becomes a very probable one."

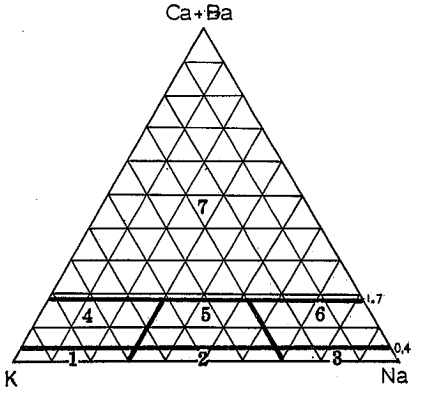
Na^+ and K^+ are large ions with small charges that can occupy this position. Ca^{2+} may occasionally occur here but only in very small amounts, possibly due to its higher charge. Ba^{2+} is very seldom reported in chemical analyses but when present it must occupy this position due to its large ionic radius.

"S" will be used to indicate the fraction of A sites filled. This position may be completely empty, as in tremolite, or completely filled, as in glaucophane. Thus S can vary from O to 1 in a 24 anion unit. Any combination of ions in this site can be indicated on the triangular diagram in text-figure 7 and represented by a "V" number.

OH Ions

One other possible variable in amphibole minerals concerns the OH^- ions. As shown in text-figure 2, two OH^- ions and 22 O^{2-} ions normally form the 24 anion unit. OH^- ions may be replaced by F^- or Cl^-. F^- has the same valence and about the same ionic radius as OH^-, and both OH^- and F^- ions are about the same size as O^{2-} ions. Cl^- has a large ionic radius and is rarely reported in amphibole analyses, and then only in very small amounts. Thus the only variable needed to define this position is an "H" number to indicate the number of OH^- ions not replaced by F^- ions.

The number of OH^- ions reported in chemical analyses varies widely, usually showing less than two OH^- per one-half unit cell but occasionally more than two. It has been suggested by Rabbitt (1948) and Hallimond (1943) that the chemical analysis procedures for H_2O are very inaccurate and there would be exactly two OH^- ions if determined accurately. Another possible explanation is loss of H^- ions with oxidation of FeO to Fe_2O_3 (basaltic hornblende) generally contain less water as seen in chemical analyses given by



TEXT-FIGURE 7.—Triangular coordinate diagram used to find the "V" number by plotting relative percentages of ions in the "A" position.

Hallimond (1943) and Winchell (1945). Hallimond (1943) suggested that some amphiboles do not contain two OH^- ions. Engel and Engel (1962) concludes that K^+ is able to replace H^+ in charge but not position, and thus is able to balance charges.

Suggested Order of Recording Variables

Variables should be arranged in a definite order for purpose of clarity and uniformity when describing an amphibole species. The following order is suggested; Y number, P number R^{3+} number, R^{2+}ab number, T number, Q^{2+}a number, Q^{1+} number, S number, V number, and H number. Although this is not the order of most importance in a classification scheme, it is a logical arrangement of the structural variables based upon increasing size of ions and coordination number.

CALCULATING NUMBER OF CATIONS

The first step in classification of an amphibole from chemical analyses is calculation of the number of cations of each type in an average half unit cell. A method used for the amphiboles is as follows:

1. Determine the relative number of oxide molecules present by dividing the weight percentages of each oxide by its molecular weight.
2. Obtain the relative number of oxygen ions each oxide contributes by multiplying the number of oxygen ions in the oxide with its relative number of oxide molecules (this does not apply to F^- or Cl^-).
3. Recalculate to half unit cell basis (24 anions) by dividing total number of oxygen ions into 24, thereby obtaining a ratio by which each oxide molecule is multiplied to obtain the number of cations per half unit cell. If the oxide contains more than one cation (i.e. Al_2O_3) multiply ratio by number of cations in oxide.

ASSIGNING IONS TO STRUCTURAL POSITION

When assigning ions to positions in the amphibole structure, all Si^{4+} ions are assigned to tetrahedral coordination and enough Al^{3+} ions are added to give the tetrahedral sites eight cations. If there is not enough Al^{3+} to make up the deficiency Fe^{3+} is added. The remaining Al^{3+}, Fe^{3+}, and any Cr^{3+}, Mn^{3+}, Ti^{4+} are assigned to octahedral coordination. Because of the charge on Ti^{4+}, the number of cations it contributes in filling octahedral sites should be doubled to maintain proper charge to site relationship. If there are more trivalent ions in octahedral position than necessary to balance electrostatic charges in the tetrahedral sites, when Ca^{2+} fills all cubic sites, then one vacant position should be allowed for each two trivalent ions. All Fe^{2+}, Mg^{2+}, Mn^{2+}, Ni^{2+}, Zn^{2+} and Li^+ are assigned to the octahedral sites if positions are available.

All Ca^{2+} is assigned to cubic coordination. If there is too much Ca^{2+} for cubic sites it may be assigned to octahedral sites if there is a vacancy. If no vacancy is present in octahedral sites then Ca^{2+} is assigned to position A. If there are too many ions for the octahedral sites, and there usually are, then Mn^{2+}, Li^+, Fe^{2+}, and Mg^{2+}, in order given, are assigned to the cubic sites if there are sites available. If not all cubic sites are filled by Ca^{2+} then enough Na^+ or K^+, in order listed, is assigned to the cubic sites to balance excess trivalent charges in octahedral coordination. The balance of Na^+ and K^+ is assigned

to position A. There may be an excess of bivalent ions in octahedral positions due perhaps to inaccurate analyses or oxidation.

To provide an example, the following chemical analysis of hornblende, (Table 3) was taken from Dana (1892) and will be classified according to the method given above.

TABLE 3
Analysis of Hornblende

Oxide	*Chem. anal. wt. %*			*Recalculated to 100 %*		*Molecular weight*		*Relative No. of oxide molecules*		*Oxygen ions*
SiO_2	40.02	X.99473	=	39.809	÷	60.06	=	0.6628	X 2	1.3256
Al_2O_3	15.55	"		15.468		101.94		0.1517	X 3	0.4551
Fe_2O_3	3.44	"		3.422		159.68		0.0214	X 3	0.0642
FeO	8.60	"		8.555		71.84		0.1191		0.1191
MgO	14.37	"		14.294		40.32		0.3545		0.3545
MnO	0.00	"		0.00		70.93		0.00		0.00
CaO	12.21	"		12.146		56.08		0.2166		0.2166
Na_2O	2.40	"		2.387		61.99		0.0385		0.0385
K_2O	2.13	"		2.118		94.19		0.0225		0.0225
H_2O	1.81	"		1.8004		18.02		0.0999		0.0999
Total	100.53									2.6960

$\frac{24}{2.696} = 8.902$ = ratio needed to determine half unit cell

Cations	*Relative No. of oxide molecules*			*Ions per 24 anions*		
Si^{4+}	0.6628	X 8.902		5.80		8.00
Al^{3+}	0.1517	"	X 2	2.70	2.20	
Fe^{3+}	0.0214	"	X 2	0.38	.50	
Mg^{2+}	0.3545	"		3.15		5.01
Fe^{2+}	0.1191	"		1.06	.98	
Ca^{2+}	0.2166	"		1.927	.08	2.007
Na^{+}	0.0385	"	X 2	0.68		
K^{+}	0.0225	"	X 2	0.40		1.08
OH^{-}	0.0999	"	X 2	1.78		1.78

Calculation of Amphibole Number for above composition

Y = number of ions of Si^{4+} replaced by Al^{3+} = 8.00 - 5.80 = 2.20

P = number of octahedral sites not filled by bivalent ions = .50 + .38 = 0.88

R^{3+} = relative percentages of trivalent ions in octahedral coordination; number obtained from figure 4 = 2

$R^{2+}ab$ = relative percentages of bivalent ions in octahedral coordination; numbers obtained from figures 3, 3a, 3b. = 2

T = number of cubic positions not filled with a bivalent ion = 0

$Q^{2+}a$ = relative percentages of bivalent ions in cubic coordination; number obtained from figures 5 & 5a. = 1

Q^{1+} = relative percentages of monovalent ions in cubic coordination; number obtained from figure 6. = 0

S = total number of ions in position A = 1

V = relative percentage of ions in position A; number obtained from figure 7. = 2

H = number of H ions not replaced by F^{-}; the number is 2 because no H ions have been replaced = 2

This species number will be found in table 2 and is assigned the name Girnarite.

PROPOSED SPECIES NAMES BASED UPON RANGES OF CRYSTAL CHEMICAL COMPOSITIONS

Although a number, as shown above and based on crystal chemical considerations, is able to describe an amphibole more completely than a name, it is customary to give names to minerals. Therefore, a variety name is assigned to many possible species numbers (Table 4). Many amphibole names in current use are associated with definite chemical and physical properties and it is essential to retain these associations. Care has been taken to assign names in agreement with original variety definitions. In some instances it has been necessary to broaden the orginal compositional range of the name, in other cases it has been necessary to considerably restrict the range to prevent extensive overlap. If several names included the same chemical composition the earliest name was retained. Names and formulae as given in Dana (1892), Hey (1955) and others were used and where necessary to expand the ranges beyond the original formulae, the extended ranges are given in parentheses in table 4. Names which had no composition given for them, such as Juddite which was described only as having a high manganese content, were assigned to appropriate divisions. Not all possible divisions were assigned names because it is not certain they exist in nature.

Nomenclature of amphiboles in the past has been based essentially upon the Y number, R^{+2}ab number, T number, Q^{+2}a number and the S number. Vague limits had been set for certain species and these limits were used whenever possible in this classification. The P, R^{+3}, Q^{+1}, and V numbers had been given no limits in original descriptions, consequently, it was necessary to assign rather large ranges to them. If an analysis shows more than one F^- ion per 24 anions the prefix "fluor" is added to the species name.

It will be noted that the name hornblende has not been used as a variety name in table 4. This name has been used in the past to cover a wide range of chemical compositions. Winchell (1942) has used hornblende to include all monoclinic amphiboles except the grunerite series and Sundius (1946) uses hornblende in about the same way. Usually any dark colored amphibole is called hornblende until it can be identified more specifically. The writer would retain the name hornblende for these particular usages.

COLLECTION AND ISOLATION OF SAMPLES

For purposes of checking the value of the proposed classification method and to gain experience in laboratory techniques, thirty samples of various amphibole minerals were obtained from several mineral supply houses in the United States. Ten specimens (Table 5) were chosen from this group for complete chemical analysis and determination of optical, X-ray powder diffraction and DTA properties. Numbers rather than the names were used to denote the specimens.

The mineral specimens were associated with many different rock types and various techniques were used to effect the isolation of the minerals. A binocular microscope, tweezers and a sharp steel point were used to separate large crystals or large pure masses from enclosing rock whenever possible. Next, the mineral was ground to 60 mesh in a mortar. A heavy liquid separation (Tetrabromoethene, sp. gr.=2.965) was used on most mineral samples. The amphiboles were just heavy enough to sink and most impurities floated to the top. Tetrabromoethene was removed from the mineral by rinsing several time

TABLE 4

Proposed amphibole variety names and corresponding species numbers

Variety	Y	P	R^{+3}	$R^{+2}ab$	T	$Q^{+2}a$	Q^{+1}	S	V
Grunerite	0-0.6	0-0.5	0,(1,2,3)	3oo	0-0.3	7ı	0,(1,2,3)	0-0.5	0,(1,2,3)
Cummingtonite	0-0.6	0-0.5	0,(1,2,3)	2oo	0-0.3	7ı	0,(1,2,3)	0-0.5	0,(1,2,3)
Kupfferite	0-0.6	0-0.5	0,(1-6)	1oo	0-0.3	72-73	0,(1,2,3)	0-0.5	0,(1,2,3)
Dannemorite	0-0.6	0-0.5	0,(1,2,3)	4oo,(5oo,6oo,7ıo)	0-0.3	7ı,(4o,6o)	0,(1,2,3)	0-0.5	0,(1,2,3)
Tremolite	0-0.6	0-0.5	0,(1,2,3)	1oo	0-0.3	1o	0,(1)	0-0.5	0,(1,2,3)
Tirodite	0-0-6	0-0.5	0,(1,2,3)	1oo	0-0.3	6o,(3o)	0,(1)	0-0.5	0,(1,2,3)
Soda-tremolite	0-0.6	0-0.5	0,(1,2,3)	1oo,(2oo)	0.3-1	1o	1,(0)	0.5-1	3,(1,2)
Byssolite	0-0.6	0-0.5	0,1,2,3	(1oo,2oo,3oo)	(0-1)	(1o)	(1,0)	(0-1)	(4,5,6,7)
Actinolite	0-0.6	0-0.5	0,(1,2,3)	2oo	0-0.3	1o	0,(1)	0-0.5	0,(1,2,3)
Ferro-tremolite	0-0.6	0-0.5	0,(2,3)	3oo	0-0.3	1o	0,(1)	0-0.5	0,(1,2,3)
Ferro-richterite	0-0.6	0-0.5	0,(2,3)	3oo,(6oo,7ıo)	0.3-1	1o,(2o,4o,5o)	1,(2)	0.5-1	3,(1,2)
Richterite	0-0.6	0-0.5	0,(1,2,3)	4oo,(1oo)	0.3-1	1o,(2o-6o)	1,(2,3)	0.5-1	2,(1,3)
Soda-richterite	0-0.6	0-0.5	0,(1,2,3)	7ıo,(5oo)	0.3-1	1o,(2o-6o)	1	0.5-1	3,(1,2)
Abkhazite	0-0.6	0-0.5	0,(1,2,3)	744	0-0.3	1o	0,(1)	0-0.5	0,(1,2,3)
Waldheimite	0.0-6	0-0.5	0,(1,2,3)	744	1.0-2	0,(1o)	1	0.5-1	3,(2)
Eckerite	0-0.6	0.5-1	3,(1,2)	4oo,(744)	0.3-1	1o,(0)	1	0-0.5	0,(1,2,3)
Eckermannite	0-0.6	0.5-1	1,3,(2)	1oo,(2oo,4oo,73o)	1.0-2	0,(1o,4o,7ı)	1	0-1	3,(0,1,2)
Mangan-tremolite	0-0.6	0-1	0,(1,2,3)	4oo,(1oo)	0-0.3	1o,(2o,4o,5o)	0,(1)	0-0.3	0,(1,2,3)
Mangan-actinolite	0-0.6	0-1	0,(1,2,3)	5oo,(2oo)	0-0.3	1o,(2o,4o,5o)	0,(1)	0-0.3	0,(1,2,3)
Grammatite	0-0.6	0-1	(4,5,6,7)	(1oo,2oo,3oo)	(0-1)	(0,1o,2o,4o)	(0,1)	(0-1)	(0,1,2,3)
Torendrikite	0-0.6	1-1.5	3,(1,2)	2oo,(1oo)	1.0-2	1o	1	0-0.5	0,(3)
Arfvedsonite	0-0.6	1-1.5	3,(2,5,6)	3oo,(2oo)	1.0-2	0,(1o)	1	0.5-1	3,(1,2)
Holmquistite	0-0.6	1.5-2	1,(2,3)	2oo,(1oo,3oo)	1.0-2	0,(1o)	4,(3,2)	0-0.5	0,(1,2,3)
Glaucophane	0-0.6	1.5-2	1,(2)	2oo	1.0-2	0,(1o)	1	0-0.5	0,(3)
Juddite	0-0.6	1.5-2	2,(1,3)	4oo,(5oo,6oo,7ıo)	1.0-2	1o-6o	1	0-0.5	0,(3)
Crossite	0-0.6	1.5-2	2,(3)	1oo	1.0-2	0,(1o)	1	0-0.5	0,(3)
Riebeckite	0-0.6	1.5-2	3,(1,2,6)	3oo	1.0-2	0,(1o-3o)	1	0-0.5	0,(2,3,1)

TABLE 4 (Cont'd.)

Ferri-tremolite	0-0.6	1.5-2	3,(2)	3oo,(2oo)	0-0.3	1o	0,(1)	0-0.5	0,(1,2,3)
Carinthine	0.6-1	0-1	1,(2)	1oo	0.3-1	1o	1	0.3-1	3
Catophorite	0.6-1	0-1	2,(1,3)	2oo	0.3-1	1o	1	0.5-1	2,(1,3)
Phillipstadite	0.6-1	0-1	3,(1,2)	2oo,(3oo)	0-0.3	1o,(4o,2o,7)	0,(1)	0-0.5	0,(1,3,2)
Anophorite	0.6-1	0-1	7,(4-6)	2oo,(1oo,3oo)	0-1	0,(1o,2o,4o)	1,(0)	0-1	3,(0,1,2)
Ferro-edenite	0.6-1	1.5-2	3,(1,2)	3oo	0-0.3	1o	0,(1)	0.5-1	3,(1,2)
Glaucopargasite	1-1.4	0.5-1	1,(2,3)	2oo,(1oo)	0-1	1o	1,(0)	0.5-1	3,(1,2)
Edenite	1.4-2	0-0.5	1,(2,3)	1oo,(2oo)	0-0.3	1o	0,(1)	0.5-1	3,(6-7)
Tibergite	1.4-2	0-0.5	0,(2,3)	1oo,(2oo,4oo,5oo)	0.3-1	1o	1	0.5-1	3,(1,2)
Pargasite	1.4-2	0.5-1	1,(2,3)	1oo,(2oo,3oo)	0-0.3	1o,(4o,5o)	0,(1)	0.5-1	3,(2,5,6)
Dashkesanite	1.4-2	0.5-1	3,(1,2)	2oo,(1oo,3oo)	0,3-1	1o,(4o)	0,(1)	0-0.5	2,(1,3)
Soretite	1.4-2	1-1.5	3,(1,2)	2oo,(1oo)	0-0.3	1o,(4o)	0,(1)	0.5-1	3,(1,2)
Kaersutite	1-2	0-1	7,6,5,4	2oo,(1oo)	0-1	1o,(4o,2o)	1,(0)	0-1	2,(3,5,6,7)
Magnesio-hastingsite	1-2	1.0-2	2,(1,3)	2oo,(1oo)	0-1	1o	1,(2,3)	0-1	2,(1,3)
Noralite	1-2	1.0-2	1,(2)	3oo	0-0.3	1o	0,(1)	0-1	0,(3)
Linosite	1-2	1-2	7,6,5,4	2oo,(1oo,3oo)	0-1	1o,(4o,2o)	1,(0)	0-1	2,(1,3)
Tschermakite	1.4-2	1.5-2	1,(2,3)	1oo,(2oo)	0-0.3	1o	0,(1)	0-0.5	0,(2,3)
Barkevikite	1.4-2	1.5-2	2,(1,3)	2oo,(1oo)	0-0.3	1o	0,(1)	0.5-1	3,(1-2)
Hudsonite	1.4-2	1.5-2	2,(3)	3oo,(2oo)	0-0.3	1o,(4o)	0,(1)	0.5-1	2,(1,3)
Ferro-tschermakite	1.4-2	1.5-2	3,(2)	3oo,(2oo)	0-0.3	1o	0,(1)	0-0.5	0,(3)
Taramite	1.4-2	1.5-2	3,(2)	3oo,(2oo)	0.3-1	1o	1,(0)	0.5-1	2,(1,3)
Bergamaskite	2-2.4	1-1.5	2,(3)	3oo	0.3-1	1o	1	0.5-1	2,(1,3)
Basaltic Hornblende	2-2.4	1.5-2	2,(1,3)	1oo,(2oo)	0.3-1	1o	1,(0)	0.5-1	2,(1,3)
Ferro-hastingsite	2-2.4	1.5-2	3,(1,2)	3oo	0.3-1	1o	1,(0,2,3)	0.5-1	2,(1,3)
Girnarite	1.4-2.4	0.5-1.5	1,2,3	2oo,(1oo,3oo)	0-1	1o,(4o,2o)	0,(1,2,3,4)	0-1	2,(1,3)
Hastingsite	2-2.4	0-2	7,6,5,4	2oo,(1oo,3oo)	0-1	1o,(4o,2o)	0,(1,2,3)	0-1	2,(1,3)
Gastaldite	1.4-2.4	2-3.5	1,(2,3)	2oo,(1oo,3oo)	0-1	7r,(o,1o,4o)	1,(0)	0-0.5	3,(1,2)
Bababudanite	2-2.4	2-2.5	3,(2,1)	2oo,(1oo,3oo)	1.0-2	0,(1o,4o)	1,(0)	0.5-1	3,(1,2)

with ethyl alcohol. Samples which contained carbonate impurities were washed for two minutes in dilute (1:5) cold hydrochloric acid. One sample was intermixed with magnetite which was removed by a small magnet. Another sample was separated from its host rock with the aid of a magnetic separator. A petrographic microscope was used to determine what impurities remained in the isolated samples and the percentage of each present. Ten grams of each sample, if available, were sent to the Mineral Constitution Laboratory at Pennsylvania State University for a chemical analysis. Enough of each sample was retained so that the physical properties of the mineral could be determined.

TABLE 5
Sample localities, preparation, and impurities

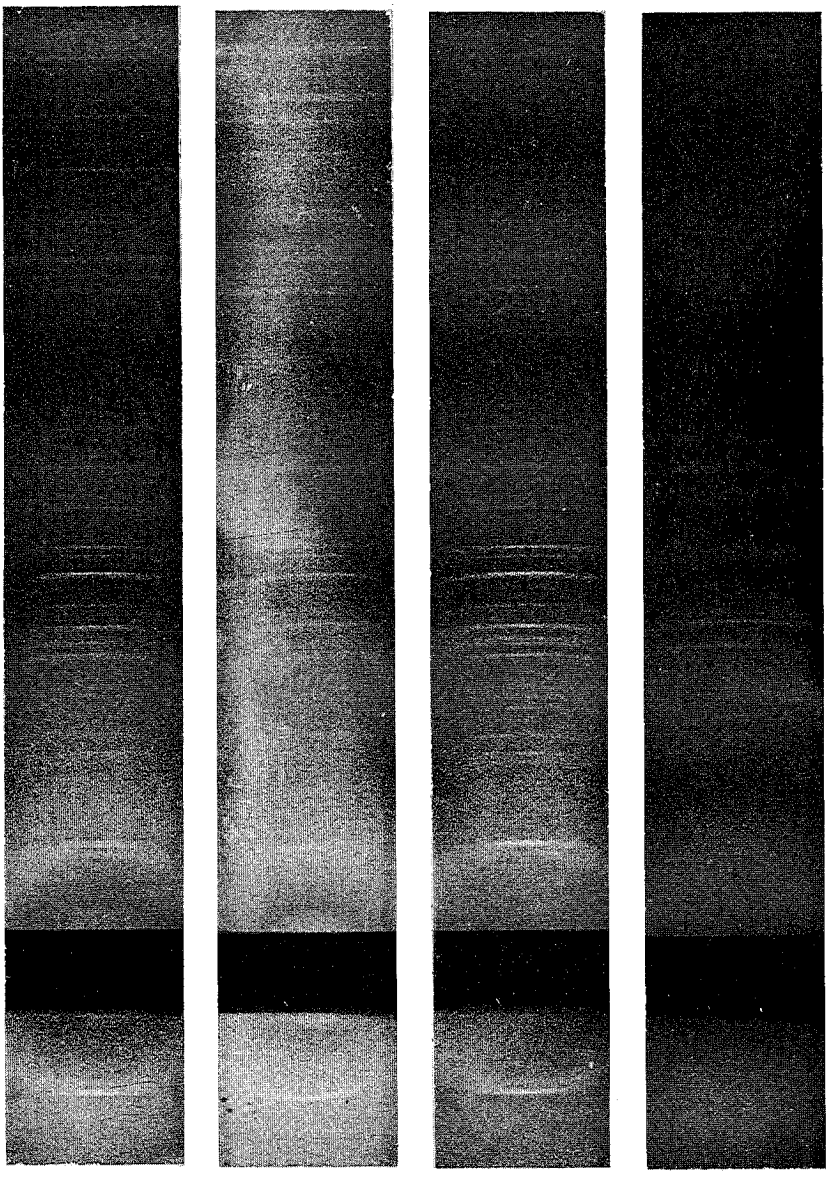
No.	*Locality*	*Methods used to isolate mineral*	*Amount and type of impurities remaining*
1	Fowler, N.Y.	Heavy liquid HCl acid	0.3% actinolite, zircon, and hornblende inclusions in tremolite
2	Chester, Vermont	Heavy liquid	0.1% tremolite
6	Nomingo mines North Bancroft, Ontario, Canada	Heavy liquid HCl acid	1% zircon
7	Verona, Ontario, Canada	Heavy Liquid	thin film, unidentified
8	Calumet mines, Chaffee County, Colorado	Heavy liquid magnet	0.2% actinolite
10	Old Colony Quarry Quincy, Norfolk County, Mass.	Heavy liquid	3% feldspar 1% quartz
13	Kragero, Norway	Heavy liquid	less than 0.1% tremolite and actinolite
18	Keystone, South Dakota	Heavy liquid	0.5% talc
19	Clay County, North Carolina	Heavy liquid	0.3% inclusions of actinolite tremolite and hornblende(?)
20	Murray Bay, Quebec, Canada		less than 1% hematite(?)

PHYSICAL PROPERTIES

Optical Properties

Optical properties of each sample were measured with a petrographic microscope and a four-axis universal stage. Index of refraction for α, β, and γ was determined, pleochroic colors described, the 2V angle and $C \wedge Z$ were measured.

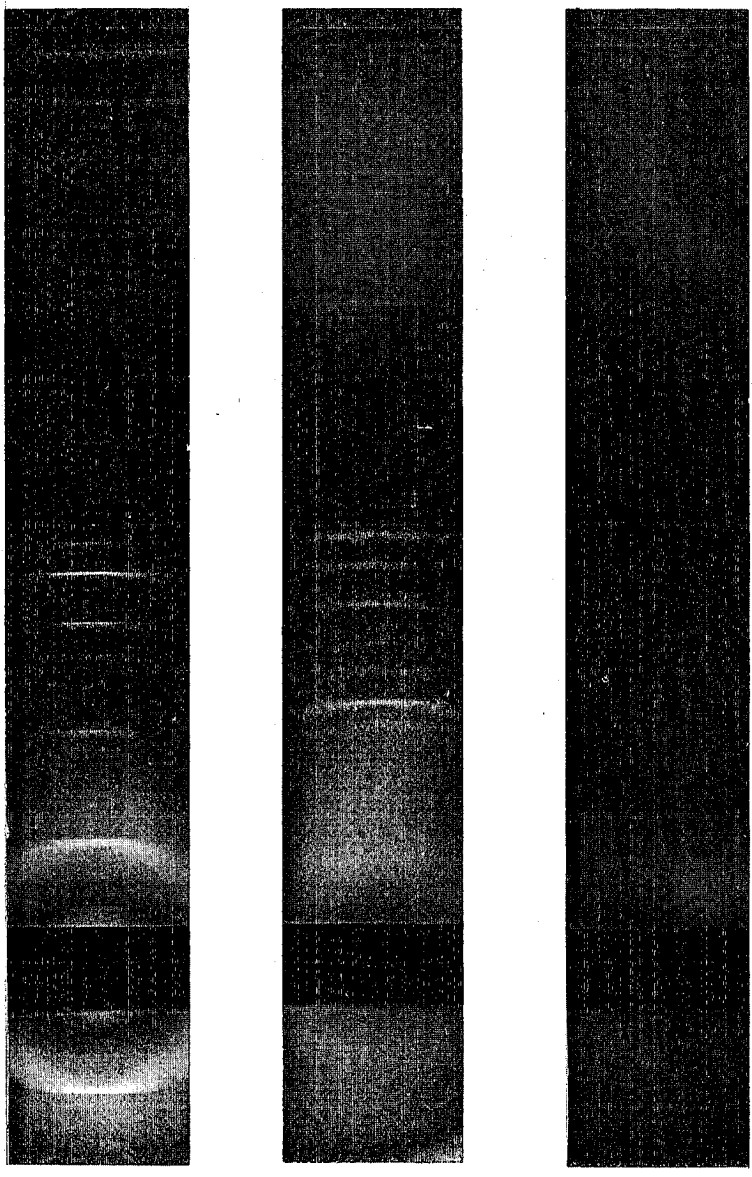
Mineral fragments, 100 mesh or smaller, were sprinkled on a moistened gelatin-coated slide which held the fragments securely in many orientations, allowing one to choose a suitably oriented fragment with which to work. Fragments which gave an optic axis centered interference figure were used in finding and measuring the index of the β ray. Pleochroic colors were also noted. Several fragments were measured and an average value calculated in each case. Fragments which had the highest birefringence and showed flash interference figures were used to measure α and γ. The index of the γ ray (negative mineral) could be measured with the cleavage of the fragments essentially parallel to the north-south direction of the microscope and α could be measured with



EXPLANATION OF PLATE 1

X-RAY POWDER PATTERNS OF SAMPLE 10

FIG. 1. Pattern of sample taken at 25° C.
FIG. 2. Pattern of same sample taken after heating to 800° C.
FIG. 3. Pattern of same sample taken after heating to 950° C.
FIG. 4. Pattern of same sample taken after heating to 1100° C.



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EXPLANATION OF PLATE 2

X-RAY POWDER PATTERNS OF SAMPLE 18

FIG. 1. Pattern of sample taken at 25° C.
FIG. 2. Pattern of same sample taken after heating to 950° C.
FIG. 3. Pattern of same sample taken after heating to 1100° C.

the fragment in an east-west position. The pleochroic colors were noted in these position.

Indices of refraction were measured by index oils using standard techniques. The mineral was bracketed with a higher and lower index oil and an average value determined. White light and central illumination were used. When cleavages, dark color, or fine-grained size made the becke line indistinct oblique illumination was used to make the fragment more conspicuous. Indices of refraction of the oils were measured with an Abbe refractometer, using a sodium vapor light source. The upper limit of the refractometer was 1.70. Oils with a higher index are recorded as labelled on the container, followed by a question mark in table 6. These values are probably too high since checked values of oils less than 1.70 were slightly too high.

The 2V angle was easily measured on sectioned fragments mounted in balsam with the 110 cleavage almost perpendicular to the slide. The 2V angles were plotted on a stereographic net and angles calculated from the net. Samples number 7 and 10 were so highly colored that they were almost opaque and the values given are only approximations. Angles from several fragments were measured and an average value determined. The angle between the acute bisectrix and the cleavage normal (C∧Z in all except sample 10) could be measured easily because of the prominent 110 cleavage in amphibole minerals. A universal stage was used for measurements.

The indices of refraction measurements are the least satisfactory of the optical measurements because the deep colors, strong absorption, dispersion, cleavages and fine-grained size make the becke line very difficult to observe. The results may be no better than ±.005 for the most intensely colored of the specimens. Table 6 summarizes observed optical values.

TABLE 6

Observed optical properties

Sample No.	*Indices*	*Birefringence*	*Pleochroism*	*2V angle*	*C Z*
1.	α = 1.598		light yellow		
	β = 1.625		very light pink		
	γ = 1.627	.029	colorless to light pink	84° (—)	—15°
2.	α = 1.621		very pale green to pink		
	β = 1.651		pale green		
	γ = 1.657	.036	medium blue-green	86° (—)	—15°
6.	α = 1.621		light yellow-green		
	β = 1.628		pale yellow-green to colorless		
	γ = 1.643	.022	pale green	86° (+)	—22°
7.	α = 1.654		very dark green		
	β = 1.701 ?		medium brown-green		
	γ = 1.720 ?	.066 ?	dark green	74° (—)	—16°
8.	α = 1.609		pale reddish-brown		
	β = 1.632		colorless to pale yellow		
	γ = 1.634	.025	light yellow-brown	88° (—)	—15°
10.	α = 1.693		medium blue-green		
	β = 1.696		dark blue-green		C∧Z
	γ = 1.730 ?	.037 ?	dark blue-green	40° ? (+)	+27 ?
13.	α = 1.629		light yellow-green		
	β = 1.650		pale green		C∧Z
	γ = 1.654	.025	medium green	88° (+ & —)	—17°

TABLE 6 (CONT.)

18.	α = 1.636		light blue-green		
	β = 1.649		pale green		
	γ = 1.662	.026	medium blue-green	86° (—)	—14°
19.	α = 1.626		pale yellow-blue		
	β = 1.643		colorless to pale yellow		
	γ = 1.671	.045	colorless to pale yellow-blue	84° (+)	—16°
20.	α = 1.621		very light yellow		
	β = 1.640		colorless		
	γ = 1.704 ?	.083 ?	pale pink	78° (+)	—4°

Fe^{2+} and Fe^{3+} seem to cause the greatest change in optical properties. This effect may be observed in a comparison of samples 1, 2, 7, and 10. Increasing Fe^{2+} and Fe^{3+}, with decreasing Mg^{2+} cause the mineral to have a blacker hand sample color, darker pleochroic colors, more opacity, higher index of refraction and smaller 2V angle. Sample 6 has a high percentage of F^- which may account for the large $C \wedge Z$. The optical properties of sample 20 are quite different from those of sample 1 although both show very similar chemical analysis. This difference must be due to the fiberous habit of sample 20. Neither the number of atoms of Si^{4+} replaced in the tetrahedral position nor the number of alkali atoms present in position "A" seem to show any observable effect upon optical properties.

X-Ray Photographs

X-ray diffraction powder photographs of each specimen were taken on a General Electric XRD-1 x-ray machine. The camera used had an eight centimeter radius and rotated the sample 360°. The mineral sample was ground in an agate mortar until fine enough to pass through a 325 mesh screen and then packed into a capillary tube with a diameter of 0.05 millimeters. Samples 1, 2 and 13, however, gave so much fluorescence that it was necessary to use a 0.02 millimeter diameter capillary tube to produce a usable photograph. Photographs were taken using iron radiation, with a $K\alpha_1$ wave length of 1.93597Å, and a manganese filter. Each photograph was exposed 2.75 hours at eleven milliampers and 30,000 volts. Spacing of each line on the film was measured by a vernier scale on a Flourline illuminated screen. Intensity of each line was estimated visually. Values are given in table 7. Repeated measurement showed the line spacing could be reproduced within 0.02 millimeters. The 002 line and 110 line were indexed by comparison to known powder patterns.

The expected increase in cell size with increase of Al^{3+} in the tetrahedral sites can not be observed in the x-ray powder patterns from these analysed samples; however, they seem to show a decrease in cell size with increase of trivalent ions in octahedral sites. A decrease in Ca^{2+} in cubic sites may also decrease cell size but the range of Ca^{2+} variation in these samples is insufficient for a good comparison. Any other relationships between chemical analysis and x-ray data are vague.

Another value of these x-ray powder photographs is to make available the patterns of several chemically analyzed amphiboles. Only six powder patterns of amphibole species could be found in the A.S.T.M. card file.

TABLE 7

X-ray powder patterns of Amphibole species

Line	*Sample No. 1*		*Sample No. 2*		*Sample No. 6*		*Sample No. 7*		*Sample No. 8*	
	d Å	I/I_0	*d Å*	I/I_0	*d Å*	I/I_0	*d Å*	I/I_0	*d Å*	I/I_0
1	1.5022	5	1.4333	25	1.5022	2	1.5097	1	1.4355	40
2	1.5103	5	1.4678	1	1.5122	2	1.5244	3	1.4997	5
3	1.5302	3	1.5009	3	1.5765	5	1.5401	1	1.5103	5
4	1.5751	8	1.5122	3	1.6159	1	1.5886	10	1.5289	1
5	1.6159	3	1.5276	3	1.6500	5	1.6235	1	1.5751	5
6	1.6476	10	1.5765	10	1.6843	1	1.6540	2	1.5966	1
7	1.6826	3	1.6182	1	1.8411	1	2.0209	1	1.6129	1
8	1.8622	3	1.6468	10	1.8654	1	2.0511	1	1.6484	5
9	1.8882	3	1.6851	1	1.8971	1	2.1679	20	1.6826	1
10	2.0118	5	1.7417	1	2.0183	3	2.2956	1	1.8600	1
11	2.0431	5	1.8622	1	2.0431	1	2.3468	20	1.8871	1
12	2.1588	15	1.8871	1	2.0458	1	†2.5531	50	2.0106	2
13	2.2734	3	2.0118	5	2.1588	10	2.6043	40	2.0391	1
14	2.2939	3	2.0405	3	2.2836	1	2.7184	100	2.1558	5
15	2.3182	3	2.1573	20	2.2991	1	2.8140	1	2.2718	1
16	2.3324	15	2.2904	1	2.3432	10	2.9493	5	2.3324	8
17	†2.5316	30	2.3112	1	2.3698	20	3.1257	80	†2.5252	50
18	2.5941	10	2.3289	15	†2.5337	40	3.2846	5	2.5862	10
19	2.7035	100	†2.5273	40	2.5930	20	3.3962	50	2.6962	100
20	2.9375	20	2.5685	80	2.7035	100	4.5366	1	2.7927	1
21	3.0992	80	2.5315	25	2.7410	1	4.9058	1	3.1058	100
22	3.2661	20	2.6624	30	2.8087	1	*8.3965	100	3.2588	10
23	3.3843	40	2.7060	100	2.9375	30			3.3725	40
24	3.8608	8	2.7980	1	3.1291	60			3.6684	20
25	4.5150	10	2.9316	40	3.3752	50			3.8713	5
26	4.8804	10	3.3725	60	3.8818	2			4.4864	5
27	5.0913	3	3.8608	5	4.5150	2			4.8720	5
28	5.3622	12	4.4935	5	4.8973	2			5.0549	2
29	*8.3713	60	4.8553	5	*8.4730	50			*8.3463	50
30	9.0501	30	5.0731	1	9.0796	8			0.0796	20
31			*8.2967	80						
32			8.4473	5						

* = 110 plane
† = 002 plane

Line	*Sample No. 10*		*Sample No. 13*		*Sample No. 18*		*Sample No. 19*		*Sample No. 20*	
	d Å	I/I_0	*d Å*	I/I_0	*d Å*	I/I_0	*d Å*	I/I_0	*d Å*	I/I_0
1	1.2893	30	1.4388	25	1.3595	25	1.4284	60	1.4361	60
2	1.3398	10	1.5028	10	1.3955	1	1.4466	2	1.4696	1
3	1.3733	8	1.5148	10	1.4306	35	1.4661	2	1.5022	1
4	1.4172	20	1.5342	1	1.4534	1	1.4941	2	1.5103	8
5	1.4608	1	1.5807	15	1.4677	1	1.5135	10	1.5329	1
6	1.4960	2	1.6174	1	1.5022	1	1.5475	2	1.5744	15
7	1.5097	5	1.6492	15	1.5148	5	1.5758	20	1.6159	1
8	1.5822	8	1.6868	1	1.5276	1	1.5996	10	1.6476	8
9	1.6047	8	1.7437	1	1.5793	30	1.6062	2	1.6843	2
10	1.6460	40	1.8654	1	1.6137	1	1.6243	2	1.8600	1

TABLE 7 (CONT.)

11	1.6893	1	1.8904	1	1.6445	25	1.6366	40	1.8882	1
12	1.7142	1	2.0170	10	1.7428	1	1.7373	5	2.0118	2
13	1.7186	1	2.0484	1	1.8611	1	1.7957	5	2.0405	1
14	1.7879	1	2.1603	30	2.0118	8	1.8547	5	2.1558	10
15	1.8516	1	2.2819	1	2.1528	15	1.8762	5	2.2768	1
16	2.0106	3	2.3360	20	2.2768	1	1.9866	2	2.2939	1
17	2.0578	2	2.5337	50	2.3324	10	1.9991	2	2.3324	10
18	2.1499	40	2.5930	40	†2.5316	40	2.0352	2	†2.5252	70
19	2.2435	2	2.7035	100	2.5795	15	2.0796	20	2.6816	5
20	2.2991	3	2.8033	5	2.6937	100	2.1410	35	2.6962	100
21	†2.5104	50	2.9375	40	3.1058	80	2.2734	2	2.8033	1
22	2.5729	3	3.1191	90	3.2478	2	2.3235	35	2.9258	20
23	2.6889	100	3.2661	40	3.3725	20	†2.5337	70	3.1091	80
24	2.9493	1	3.3882	50	3.6684	15	2.6864	100	3.2551	5
25	3.0570	70	3.8765	1	3.8871	1	2.7720	2	3.3607	40
26	3.2155	1	4.5150	3	4.5078	2	2.9142	30	3.8765	1
27	3.3607	20	4.9058	5	4.8973	2	3.0828	90	4.4794	3
28	3.8197	1	*8.3463	80	*8.4219	50	3.2370	25	4.8636	3
29	4.4030	25	9.0208	5	8.5771	3	3.3491	40	*8.5247	30
30	7.9655	90					3.8608	2	9.0796	3
31	*8.2967	80					4.4513	2		
32							4.8636	2		
33							*8.2234	50		
34							8.9629	8		

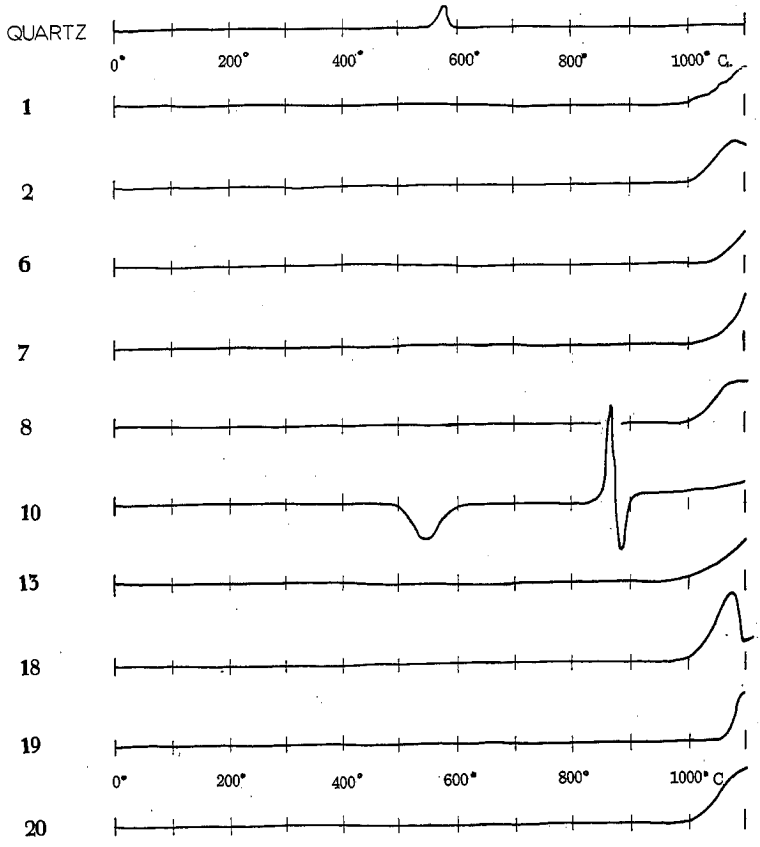
* = 110 plane
† = 002 plane

Differential Thermal Analyses

Equipment used consisted of a Hoskins electric furnace capable of producing temperatures up to 1100°C, controlled by a continuously variable autotransformer made by General Radio. A thermocouple recorded the temperature of the furnace through a Leeds and Northrup Micromax. A differential thermocouple, consisting of two chromel wires connected by an alumel wire, recorded the differential temperature between the mineral sample and pure Al_2O_3 through a six channel Minneapolis Honeywell recorder. The mineral sample was ground fine enough to pass through a 100 mesh screen, then packed tightly into a cavity, $\frac{1}{4}$ inch by $\frac{3}{4}$ inch, in the heating block. Quartz was simultaneously run for control and comparison. The variac was adjusted so that it required two hours to raise the temperature from 20° to 1100°C. Repeated heating of one sample indicated the position of the peak with respect to the temperature was reproducable within 10°C, but, amplitude of the peak was variable.

Only two of the ten samples, 10 and 18, show a complete endothermic reaction below 1100°C. Only sample 10 shows an exothermic reaction below 1100°C, a broad curve at 550°C and a sharp peak at 890°C. The other specimens have endothermic reactions above 1100°C (Text-fig. 8).

X-ray diffraction powder photographs of samples 10, and 18 were taken before and after the endothermic reactions. Several samples were analyzed for percent of FeO and Fe_2O_3 at various temperatures, to determine causes of endothermic reactions. Table 9 shows oxidation takes place gradually throughout the heating at least at the heating rate used in these tests.



TEXT-FIGURE 8. —Differential thermal curves of studied amphiboles.

TABLE 8

X-ray powder patterns of samples 10 and 18 at higher temperatures

Line	*Sample No. 18 at 950°C*		*Sample No. 18 at 1100°C*		*Sample No. 10 at 800°C*		*Sample No. 10 at 950°C*		*Sample No. 10 at 1100°C*	
	d Å	*I/I₀*	*d Å*	*I/I₀*	*d Å*	*I/I₀*	*d Å*	*I/I₀*	*d Å*	*I/I₀*
1	1.4268	30	1.4099	1	1.2799	20	1.4528	10	1.2603	10
2	1.5122	2	1.4637	1	1.3336	15	1.4826	10	1.3100	10
3	1.5772	20	1.6197	1	1.3647	2	1.6910	20	1.4540	40
4	1.6382	5	1.7400	1	1.4062	2	1.8349	10	1.4856	30
5	1.6859	1	2.0299	5	1.4899	2	2.2003	5	1.6935	50
6	1.8632	1	2.1263	10	1.5028	2	2.5104	55	1.8432	20
7	2.0055	1	2.2209	1	1.5556	2	2.6816	50	2.5104	30
8	2.1484	2	2.5295	30	1.5765	2	2.8913	5	2.6986	30
9	2.2751	2	2.9084	25	1.6382	10	2.9762	40		
10	2.2973	1	2.9884	80	2.1410	40	3.3260	5		

TABLE 8 (CONT.)

11	2.3289	10	3.1908	50	2.5038	25	3.6637	5
12	2.5316	80	3.7062	5	2.6913	100	4.0696	60
13	2.5862	40	4.0238	5	3.0538	50		
14	2.6365	2			3.3491	30		
15	2.6937	100			4.4305	5		
16	3.0861	70			8.1993	80		
17	3.2551	2						
18	3.3725	50						
19	3.8818	3						
20	4.0523	2						
21	4.5150	3						
22	4.8804	2						
23	8.3214	90						
24	9.1994	3						

TABLE 9

Percentages of FeO vs. Fe_2O_3 at selected temperatures to determine degree of oxidation

Sample	*Percent*	
No. 10	*FeO*	*Fe_2O_3*
@ 450°C	16.94	13.99
@ 630°C	7.17	25.47
@ 930°C	1.07	32.86
No. 18		
@ 700°C	8.22	2.34
@ 900°C	3.78	7.12
@ 1100°C	0.70	11.84

Plates 1 and 2 shows x-ray diffraction patterns before and after reaction. It can be seen that there has been a structural change but not a complete breakdown of the structure in sample 10 even though it was heated until fused, at a temperature less than 1100°C. Thus the reaction seems to be due essentially to structural change and not to oxidation of Fe^{2+} to Fe^{3+}.

Chemical analyses do not show exactly what determines the ease of the endothermic-exothermic reactions. Anaylses seem to indicate that low concentration of Ca^{2+} and high concentrations of Na^{+} and K^{+} may lower the temperature at which the reactions take place.

Works by Wittels (1952) and Korzhinskii (1961) indicate dehydration products of amphiboles may contain various mixtures of two or more of the following products depending upon the variety of the amphibole: magnetite, maghemite, olivine, plagioclase, glass, several varieties of pyroxene, cristobalite, hematite, and water.

Chemical Analyses

The ten amphibole samples were analyzed at the Pennsylvania Experiment Station by C.O. Ingamells (See Tables 10-18). It was hoped that chemical composition could be related to physical properties, but only Fe^{2+} and Fe^{3+}

seem to show any possible correlation in these ten samples. Ten samples may be too few to permit any visible trends.

As in most amphibole analysis, it can be seen that the number of OH^- ions is variable, sometimes more than two and sometimes less than two. Except for samples 7 and 20, there is an excess of positive ions when there are more than 2 OH^- ions and a deficiency of positive ions when there are less than 2 OH^- ions. Samples 13 and 6, which are very deficient in OH^- ions, were reported to probably contain Cl^- ions but were not analyzed for Cl^-.

BaO and SrO were reported not present in appreciable amounts. Sample 2 was reported to contain B_2O_3. This was probably an impurity and may explain the deficiency of ions in the octahedral and cubic sites. ZrO_2 was reported as present and included with the Al_2O_3. It was probably present as an impurity.

SUMMARY AND CONCLUSIONS

Ten amphibole samples were analyzed chemically and their sturctural composition calculated to determine how well they fit the classification developed in this paper. They correlated well as is shown by their name and number.

Optical, X-ray, and DTA properties of these ten samples were determined in an attempt to relate physical properties to chemical composition. Fe^{2+} and Fe^{3+} gave the mineral higher refractive index, smaller 2V angle, and darker pleochroic colors. Fluoride ions seem to increase C∧Z. Neither replacement of Si^{4+} in tetrahedral sites, nor introduction of alkali ions in position "A" have any effect upon optical properties. Substitution of Al^{3+} for Si^{4+} in tetrahedral coordination did not give a larger cell size as can be seen from the X-ray patterns, but, an increase of trivalent ions in octahedral sites and a decrease of Ca^{2+} in cubic sites cause the species to show a smaller cell size. DTA curves show oxidation and hydration take place gradually all along the heating curve. The structure does not break down, up to temperatures of 1100°C, but, there is a shift of X-ray lines. A decrease in the amount of Ca^{2+} present and an increase of Na^+ and K^+ lower the temperature at which the endothermic reaction takes place.

Only six powder patterns of amphibole species are in the ASTM card file. Now ten more powder patterns of chemically analyzed species are available. Also, X-ray patterns are included which show a shift in the structure as the mineral is heated. DTA curves are now available for analysed amphibole minerals showing an endothermic reaction due to structure change that, for most amphiboles, takes place above 1100°C. The relationship between valence, chemical composition, and structural position can now be clearly shown by use of the number system developed in this paper.

The current study indicated there is not enough correlation between chemical composition and physical properties to be useful in a definitive classification. If a larger number of samples were analyzed, however, some meaningful trends may appear which would be useful in defining the many variables now operating. Any future advances in a method to give reasonably good chemical analysis much more quickly and less expensively would be very helpful, even necessary, for the greatest usefulness of this classification. At the present time good chemical analyses cost about $125.00 per sample and require months for a complete analysis. If emission spectroscopy or X-ray fluorescence could give more quantitative results minerals could be analyzed much more rapidly and the proposed classification made more useful.

TABLE 10

Analytical data and structural composition of sample 1

Oxide	*Chem. anal. wt. %*	×	*Correction*	=	*Recalculated to 100%*	÷	*Molecular weight*	=	*Relative No. of oxide molecules*		*Oxygen ions*
SiO_2	58.60	X	1.0008	=	58.65	÷	60.06	=	.9752	X 2	1.9508
Al_2O_3	.52		"		0.52		101.94		.0051	X 3	.0153
Fe_2O_3							159.68				
TiO_2	.04		"		0.04		79.90		.0005	X 2	.0010
V_2O_5							181.90				
Cr_2O_3							152.02				
FeO	.22		"		0.22		71.84		.0031		.0031
NiO							74.71				
MnO	.50		"		0.52		70.93		.0073		.0073
MgO	24.66		"		24.68		40.32		.6121		.6121
Li_2O	.06		"		0.06		29.88		.0020		.0020
CaO	12.26		"		12.27		56.08		.2188		.2188
Na_2O	.73		"		0.70		61.99		.0113		.0113
K_2O	.16		"		0.16		94.19		.0017		.0017
H_2O^-	.01		"		0.01		18.02		.0006		.0006
H_2O^+	1.89		"		1.89		18.02		.1048		.1048
F	.42		"		0.42		19.00		.0221		.0221
P_2O_5	.01		"		0.01		141.95		.0001		.0001
	100.08										2.9510
O=F	.16				24	=	8.130	=	ratio needed for one-half unit cell		
					2.9510						
Total	99.92										

Cations	*Relative No. of oxide molecules*	*Ratio*			*Ions per 24 anions*	
Si^{4+}	.9754	X 8.13	X 1	=	7.93	]
Al^{3+}	.0051	"	X 2		0.04	] 7.974
Ti^{4+}	.0005	"	X 1		0.004	]
Mg^{2+}	.6121	"	X 1		4.98	] 4.98
Fe^{2+}	.0031	"	X 1		0.03	]
Mn^{2+}	.0073	"	X 1		0.06	]
Ca^{2+}	.2188	"	X 1		1.78	] 1.993
Li^{1+}	.0002	"	X 2		0.003	]
Na^{1+}	.0113	"	X 2		0.09	]
K^{1+}	.0017	"	X 2		0.03	]
OH^-	.1048	"	X 2		1.70	]
F^-	.0221	"	X 1		0.18	] 1.88

Composition Number = 0.044, 0, 0, 1oo, 0.12, 1o, 1, 0, 0, 1.82
Name - Tremolite

TABLE 11

Analytical data and structural composition of sample 2

Oxide	*Chem. anal. wt. %*	× *Correction*	*Recalculated to 100%*	÷ *Molecular weight*	= *Relative No. of oxide molecules*	*Oxygen ions*
SiO_2	55.60	X 1.0003	= 55.62	60.06	.9261 X 2	1.8522
Al_2O_3	2.41	"	2.41	101.94	.0236 X 3	.0708
Fe_2O_3	1.55	"	1.55	159.68	.0097 X 3	.0291
TiO_2				79.90		
V_2O_5	.02	"	0.02	181.90	.0001 X 5	.0005
Cr_2O_3	.27	"	0.27	152.02	.0017 X 3	.0051
FeO	4.81	"	4.81	71.84	.0670	.0670
NiO	.17	"	0.17	74.71	.0023	.0023
MnO	.32	"	0.32	70.93	.0045	.0045
MgO	20.31	"	20.32	40.32	.5040	.5040
Li_2O	.01	"	0.01	29.88	.0003	.0003
CaO	11.90	"	11.90	56.08	.2122	.2122
Na_2O	.55	"	0.55	61.99	.0089	.0089
K_2O	.07	"	0.07	94.19	.0008	.0008
H_2O^-				18.02		
H_2O^+	1.92	"	1.92	18.02	.1065	.1065
F^-	.11	"	0.11	19.00	.0058	.0058
P_2O_5				141.95		
	100.02					2.8700
O=F	.05					
Total	99.97					

$\frac{24}{2.8700} = 8.36$ ratio needed for one-half unit cell

Note: analyst reported some Zn_2^+ present

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.9261	X 8.36	X 1	7.74	0.26	8.00
Al^{3+}	.0236	"	X 2	0.395	0.13	
Fe^{3+}	.0097	"	X 2	0.13		4.96
Cr^{3+}	.0017	"	X 2	0.03		
Mg^{2}	.5040	"	X 1	4.21		
Fe^{2+}	.0670	"	X 1	0.56		
Mn^{2+}	.0045	"	X 1	0.04		
Ni^{2+}	.0023	"	X 1	0.02		
Li^{1+}	.0003	"	X 2	0.004		1.994
Ca^{2+}	.2122	"	X 1	1.77		
Na^{1+}	.0089	"	X 2	0.15		
K^{1+}	.0008	"	X 2	0.01		
OH^-	.1065	"	X 2	1.78		1.83
F^-	.0058	"	X 1	0.05		

Composition Number = 0.26, 0.16, 5, 1oo, 0.16, 1o, 1, 0, 0, 1.95
Name - Grammatite

TABLE 12

Analytical data and structural composition of sample 6

Oxide	*Chem. anal. wt. %*	×	*Correction*	=	*Recalculated to 100%*	÷	*Molecular weight*	=	*Relative No. of oxide molecules*		*Oxygen ions*
SiO_2	53.23	X	1.0042	=	53.45		60.06		.8899	X 2	1.7798
Al_2O_3	3.62		"		3.64		101.94		.0357	X 3	.1071
Fe_2O_3	1.92		"		1.93		159.68		.0123	X 3	.0369
TiO_2	.15		"		0.15		79.90		.0019	X 2	.0038
V_2O_5							181.90				
Cr_2O_3							152.02				
FeO	2.59		"		2.60		71.84		.0362		.0362
NiO							74.71				
MnO	.20		"		0.20		70.93		.0028		.0028
MgO	21.17		"		21.26		40.32		.5273		.5273
Li_2O	.01		"		0.01		29.88		.0003		.0003
CaO	11.74		"		11.79		56.08		.2102		.2102
Na_2O	2.12		"		2.13		61.99		.0343		.0343
K_2O	.98		"		0.98		94.19		.0104		.0104
H_2O^-							18.02				
H_2O^+	.68		"		0.68		18.02		.0377		.0377
F	2.18		"		2.19		19.00		.1153		.1153
P_2O_5							141.95				
	100.59										2.9021
O=F	1.01										
Total	99.58										

$\frac{24}{2.9021} = 8.27$ ratio needed for one-half unit cell

Note: analyst reported some Cl^- present

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.8899	X 8.27	X 1	7.36		8.00
Al^{3+}	.0357	"	X 2	0.59	.05	
Fe^{3+}	.0123	"	X 2	0.20	.15	
Ti^{4+}	.0019	"	X 1	0.02		5.005
Mg^{2+}	.5273	"	X 1	4.36		
Fe^{2+}	.0362	"	X 1	0.30		
Mn^{2+}	.0028	"	X 1	0.02		
Li^{1+}	.0003	"	X 2	0.005	.13	
Ca^{2+}	.2102	"	X 1	1.74	1.61	2.00
Na^{1+}	.0343	"	X 2	0.57	.39	
					.18	.35
K^{1+}	.0104	"	X 2	0.17		
OH^-	.0377	"	X 2	0.62		1.57
F^+	.1153	"	X 1	0.95		

Composition Number = 0.64, 0.17, 6, 1oo, 0.39, 1o, 1, 0.35, 2, 1.05
Name - Anophorite

TABLE 13

Analytical data and structural composition of sample 7

Oxide	*Chem. anal. wt. %*	×	*Correction*	=	*Recalculated to 100%*	÷ *Molecular weight*	=	*Relative No. of oxide molecules*		*Oxygen ions*
SiO_2	41.03	X	1.0008	=	41.06	60.06		.6836	X 2	1.3672
Al_2O_3	10.82		"		10.83	101.94		.1062	X 3	.3186
Fe_2O_3	7.53		"		7.54	159.68		.0472	X 3	.1416
TiO_2	.77		"		0.77	79.90		.0096	X 2	.0192
V_2O_5	.02		"		0.02	181.90		.0001	X 5	.0005
Cr_2O_3						152.02				
FeO	16.10		"		16.11	71.84		.2242		.2242
NiO										
MnO	.97		"		0.97	70.93		.0136		.0136
MgO	7.12		"		7.13	40.32		.1768		.1768
Li_2O	.03		"		0.03	29.88		.0010		.0010
CaO	10.04		"		10.05	56.08		.1792		.1792
Na_2O	1.49		"		1.45	61.99		.0234		.0234
K_2O	1.71		"		1.71	94.19		.0185		.0185
H_2O^-	.10		"		0.10	18.02		.0055		.0055
H_2O^+	1.83		"		1.83	18.02		.1015		.1015
F	.59		"		0.51	19.00		.0270		.0270
P_2O_5	.01		"		0.01	141.95		.0000		
	100.16									2.6138
O=F	.24									
Total	99.92									

$$\frac{24}{2.6138} = 9.18$$ ratio needed for one-half unit cell

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.6836	X 9.18	X 1	6.27	1.73	8.00
Al^{3+}	.1062	"	X 2	1.95	.22	
Fe^{3+}	.0472	"	X 2	0.87		5.00
Ti^{4+}	.0096	"	X 1	0.09		
Mg^{2+}	.1768	"	X 1	1.62		
Fe^{2+}	.2242	"	X 1	2.06		
Li^{1+}	.0010	"	X 2	0.002	.05	
Mn^{2+}	.0136	"	X 1	0.12	.07	2.00
Ca^{2+}	.1792	"	X 1	1.65	.28	
Na^{1+}	.0234	"	X 2	0.43	.15	.49
K^{1+}	.0185	"	X 2	0.34		
OH^-	.1015	"	X 1	1.86		2.11
F^-	.0270	"	X 1	0.25		

Composition Number = 1.73, 1.18, 3, 2oo, 0.28, 1o, 1, 0.49, 1, 1.75
Name - Magnesio-hastingsite

TABLE 14

Analytical data and structural composition of sample 8

Oxide	*Chem. anal. wt. %*	× *Correction*	= *Recalculated to 100%*	÷ *Molecular weight*	= *Relative No. of oxide molecules*	*Oxygen ions*
SiO_2	57.57	X 1.0020	57.68	60.06	.9605 X 2	1.9210
Al_2O_3	1.02	"	1.02	101.94	.0100 X 3	.0300
Fe_2O_3	.70	"	0.70	159.68	.0044 X 3	.0132
TiO_2	.08	"	0.08	79.90	.0010 X 2	.0020
V_2O_5						
Cr_2O_3						
FeO	2.79	"	2.80	71.84	.0389	.0389
NiO						
MnO	.14	"	0.14	70.93	.0020	.0020
MgO	22.59	"	22.64	40.32	.5615	.5615
Li_2O	.01	"	0.01	29.88	.0004	.0004
CaO	12.34	"	12.36	56.08	.2204	.2204
Na_2O	.18	"	0.18	61.99	.0029	.0029
K_2O	.13	"	0.13	94.19	.0014	.0014
H_2O^-	.04	"	0.04	18.02	.0022	.0022
H_2O^+	2.05	"	2.05	18.02	.1138	.1138
F	.23	"	0.23	19.00	.0126	.0126
P_2O_5	.01	"	0.01	141.95	.0000	
	99.88					2.9223
O=F	.08					
Total	99.80					

$\frac{24}{2.9223} = 8.21$ ratio needed for one-half unit cell

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.9605	X 8.21	X 1	7.89	.11	8.00
Al^{3+}	.0100	"	X 2	0.16	.05	
Fe^{3+}	.0044	"	X 2	0.07		5.00
Ti^{4+}	.0010	"	X 1	0.01		
Mg^{2+}	.5615	"	X 1	4.61		
Fe^{2+}	.0389	"	X 1	0.32	.25	
Li^{1+}	.0004	"	X 2	0.006	0.7	
Ca^{2+}	.2204	"	X 1	1.81		1.956
Na^{1+}	.0029	"	X 2	0.05		
K^{1+}	.0014	"	X 2	0.02		
OH^-	.1138	"	X 2	1.87		1.97
F^-	.0126	"	X 1	0.10		

Composition Number = 0.11, 0.13, 2, 1oo, 0.08, 1o, 1, 0, 0, 1.90
Name - Mangan-tremolite

TABLE 15

Analytical data and structural composition of sample 10

Oxide	*Chem. anal. wt. %*	× *Correction*	= *Recalculated to 100%*	÷ *Molecular weight*	= *Relative No. of oxide molecules*		*Oxygen ions*
SiO_2	50.77	X 1.0008	= 50.81	60.06	.8459	X 2	1.6918
Al_2O_3	2.32	"	2.32	101.94	.0228	X 3	.0684
Fe_2O_3	14.35	"	14.36	159.68	.0899	X 3	.2697
TiO_2	1.41	"	1.41	79.90	.0177	X 2	.0354
V_2O_5							
Cr_2O_3							
FeO	20.16	"	20.18	71.84	.2809		.2809
NiO							
MnO	.47	"	0.47	70.93	.0066		.0066
MgO	.07	"	0.07	40.32	.0017		.0017
Li_2O	.27	"	0.27	29.88	.0090		.0090
CaO	1.02	"	1.02	56.08	.0183		.0183
Na_2O	5.95	"	5.95	61.99	.0960		.0960
K_2O	1.27	"	1.20	94.19	.0128		.0128
H_2O^-	.03	"	0.03	18.02	.0017		.0017
H_2O^+	1.59	"	1.59	18.02	.0882		.0882
F	.40	"	0.40	19.00	.0211		.0211
P_2O_5	.01	"	0.01	141.95	.0000		
	100.09						2.6015
O=F	.17						
Total	99.92						

$$\frac{24}{2.6015} = 9.23$$ ratio needed for one-half unit cell

Note: analyst reported some Zn_2^+ present

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.8495	X 9.23	X 1	7.84	.16	8.00
Al^{3+}	.0228	"	X 2	0.42	.26	
Fe^{3+}	.0899	"	X 2	1.66		
Ti^{4+}	.0177	"	X 1	0.16		5.00
Mg^{2+}	.0017	"	X 1	0.02		
Fe^{2+}	.2809	"	X 1	2.59	.15	
Li^{1+}	.0090	"	X 2	0.17	0.2	
Mn^{2+}	.0066	"	X 1	0.06		2.00
Ca^{2+}	.0182	"	X 1	0.17	1.75	
Na^{1+}	.0960	"	X 2	1.77	.02	
K^{1+}	.0128	"	X 2	0.24		0.26
OH^-	.0882	"	X 2	1.63		1.82
F^-	.0211	"	X 1	0.19		

Composition Number = 0.16, 2.23, 3, 300, 1.77, 30, 1, 0.26, 1, 1.81
Name - Riebeckite

TABLE 16

Analytical data and structural composition of sample 13

Oxide	*Chem. anal. wt. %*	× *Correction*	*Recalculated to 100%*	÷ *Molecular weight*	= *Relative No. of oxide molecules*	*Oxygen ions*
SiO_2	51.44	X 1.0041 =	51.65	60.06	.8597 X 2	1.7194
Al_2O_3	5.49	"	5.51	101.94	.0541 X 3	.1623
Fe_2O_3	2.84	"	2.85	159.68	.0178 X 3	.0534
TiO_2	.95	"	0.95	79.90	.0119 X 2	.0238
V_2O_5	.05	"	0.05	181.90	.0003 X 5	.0015
Cr_2O_3						
FeO	4.97	"	4.99	71.84	.0681	.0681
NiO						
MnO	.04	"	0.04	70.93	.0005	.0005
MgO	18.75	"	18.82	40.32	.4667	.4667
Li_2O	.02	"	0.02	29.88	.0007	.0007
CaO	10.80	"	10.84	56.08	.1933	.1933
Na_2O	2.14	"	2.15	61.99	.0347	.0347
K_2O	.29	"	0.29	94.19	.0031	.0031
H_2O^-	.01	"	0.01	18.02	.0004	.0004
H_2O^+	1.68	"	1.69	18.02	.0938	.0938
F	.20	"	0.20	19.00	.0105	.0105
P_2O_5	.01	"	0.01	141.95	.0000	
	99.67					2.8322
O=F	.08					
Total	99.59					

$$\frac{24}{2.8322} = 8.47$$ ratio needed for one-half unit cell

Note: analyst reported some Cl^- present

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.8597	X 8.47	X 1	7.28	.72	8.00
Al^{3+}	.0541	"	X 2	0.92	.20	
Fe^{3+}	.0078	"	X 2	0.30		5.005
Ti^{4+}	.0119	"	X 1	0.10		
V^{5+}	.0003	"	X 2	0.005		
Mg^{2+}	.4667	"	X 1	3.95	.35	
Fe^{2}	.0681	"	X 1	0.58	.23	
Mn^{2+}	.0005	"	X 1	0.004		2.00
Li^{1+}	.0007	"	X 2	0.01		
Ca^{2+}	.1933	"	X 1	1.63	.13	
Na^{1+}	.0347	"	X 2	0.59	.46	.51
K^{1+}	.0031	"	X 2	0.05		
OH^-	.0938	"	X 2	1.59		1.68
F^-	.0105	"	X 1	0.09		

Composition Number = 0.72, 0.60, 5, 1oo, 0.14, 4o, 1, 0.51, 3, 1.91

Name - Anophorite

TABLE 17
Analytical data and structural composition of sample 18

Oxide	*Chem. anal. wt. %*	× *Correction*	= *Recalculated to 100%*	÷ *Molecular weight*	= *Relative No. of oxide molecules*	*Oxygen ions*
SiO_2	49.53	X 1.0027	49.66	60.06	.8268 X 2	1.6536
Al_2O_3	9.92	"	9.95	101.94	.0977 X 3	.2931
Fe_2O_3	1.10	"	1.10	159.68	.0069 X 3	.0207
TiO_2	.59	"	0.50	79.90	.0063 X 2	.0126
V_2O_5	.04	"	0.04	181.90	.0002 X 5	.0010
Cr_2O_3	.06	"	0.06	152.02	.0004 X 3	.0012
FeO	10.59	"	10.62	71.84	.1478	.1478
NiO	.02	"	0.02	74.71	.0003	.0003
MnO	.26	"	0.26	70.93	.0036	.0036
MgO	14.64	"	14.68	40.32	.3641	.3641
Li_2O	.01	"	0.01	29.88	.0003	.0003
CaO	9.75	"	9.78	56.08	.1744	.1744
Na_2O	1.01	"	1.01	61.99	.0163	.0163
K_2O	.17	"	0.17	94.19	.0018	.0018
H_2O^-						
H_2O^+	2.00	"	2.01	18.02	.1115	.1115
F	.01	"	0.01	19.00	.0005	.0005
P_2O_5	.03	"	0.03	141.95	.0002 X 5	.0010
	99.73					2.8038
O=F	.00					
Total	99.73					

$\frac{24}{2.8038} = 8.56$ ratio needed for one-half unit cell

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.8268	X 8.56	X 1	7.08	.92	8.00
Al^{3+}	.0977	"	X 2	1.67	.75	
Fe^{3+}	.0069	"	X 2	0.12		
Ti^{4+}	.0063	"	X 1	0.05		
V^{5+}	.0002	"	X 2	0.003		5.00
Cr^{3+}	.0004	"	X 2	0.006		
Mg^{2+}	.3641	"	X 1	3.12	.90	
Fe^{2+}	.1478	"	X 1	1.27	.37	
Ni^{2+}	.0003	"	X 1	0.003		
Mn^{2+}	.0036	"	X 1	0.03		2.00
Li^{1+}	.0003	"	X 2	0.005		
Ca^{2+}	.1744	"	X 1	1.49	.10	
Na^{1+}	.0163	"	X 2	0.28	.18	
K^{1+}	.0018	"	X 2	0.03		.21
OH^-	.1115	"	X 2	1.91		
F^-	.0004	"	X 1	0.004		1.91

Composition Number = 0.92, 0.92, 1, 2oo, 0.10, 7i, 1, 0.21, 3, 2
Name - Phillipstadite

TABLE 18

Analytical data and structural composition of sample 19

Oxide	*Chem. anal. wt. %*	× *Correction*	*Recalculated to 100%*	÷ *Molecular weight*	= *Relative No. of oxide molecules*	*Oxygen ions*
SiO_2	45.34	X 1.0011 =	45.39	60.06	.7557 X 2	1.5114
Al_2O_3	18.66	"	18.68	101.94	.1832 X 3	.5496
Fe_2O_3	.41	"	0.41	159.68	.0026 X 3	.0078
TiO_2	.02	"	0.02	79.70	.0003 X 2	.0006
V_2O_5						
Cr_2O_3	.22	"	0.22	152.02	.0014 X 3	.0042
FeO	3.14	"	3.14	71.84	.0437	.0437
NiO	.11	"	0.11	74.71	.0015	.0015
MnO	.06	"	0.06	70.93	.0008	.0008
MgO	16.36	"	16.38	40.32	.4062	.4062
Li_2O	.01	"	0.01	29.88	.0003	.0003
CaO	12.21	"	12.22	56.08	.2179	.2179
Na_2O	1.19	"	1.19	61.98	.0192	.0192
K_2O	.16	"	0.16	94.19	.0017	.0017
H_2O^-						
H_2O^+	1.99	"	1.99	18.02	.1104	.1104
F						
P_2O_5	.01	"	0.01	141.95	.0000	
	99.89					2.8733
O=F	.00					
Total	99.89					

$\frac{24}{2.8733} = 8.35$ ratio needed for one-half unit cell

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*		
Si^{4+}	.7557	X 8.35	X 1	6.31	1.69	8.00
Al^{3+}	.1832	"	X 2	3.06	1.37	
Fe^{3+}	.0026	"	X 2	0.04		
Ti^{4+}	.0003	"	X 1	0.003		
Cr^{3+}	.0014	"	X 2	0.02		5.006
Mg^{2+}	.4062	"	X 1	3.39	.18	
Fe^{2+}	.0437	"	X 1	0.36	.18	
Mn^{2+}	.0008	"	X 1	0.007		
Li^{1+}	.0003	"	X 2	0.005		2.002
Ni^{2+}	.0015	"	X 1	0.01		
Ca^{2+}	.2179	"	X 1	1.82	1.80	
Na^{1+}	.0192	"	X 2	0.32	.02	
K^{1+}	.0017	"	X 2	0.03		.37
OH^-	.1104	"	X 2	1.84		1.84

Composition Number = 1.69, 141, 1, 1oo, 0, 4o, 4, 0.37, 3, 2
Name - Girnarite

TABLE 19
Analytical data and structural composition of sample 20

Oxide	*Chem. anal. wt. %*	×	*Correction*	=	*Recalculated to 100%*	÷ *Molecular weight*	=	*Relative No. of oxide molecules*		*Oxygen ions*
SiO_2	59.92	X	1.0014	=	60.00	60.06		.9990	X 2	1.9980
Al_2O_3										
Fe_2O_3										
TiO_2										
V_2O_5										
Cr_2O_3										
FeO	.08		"		0.80	71.84		.0111		.0111
NiO										
MnO	.03		"		0.03	70.93		.0004		.0004
MgO	24.36		"		24.39	40.32		.6049		.6049
Li_2O	.01		"		0.01	29.88		.0003		.0003
CaO	13.38		"		13.40	56.08		.2389		.2389
Na_2O	.12		"		0.12	61.98		.0019		.0019
K_2O	.02		"		0.02	94.19		.0002		.0002
H_2O^-										
H_2O^+	2.19		"		2.19	18.02		.1210		.1210
F	.05		"		0.05	19.00		.0263		.0263
P_2O_5										
	99.88									3.0030
O=F	.02									
Total	99.86									

$\frac{24}{3.0030} = 7.99$ ratio needed for one-half unit cell

Cations	*Relative No. of oxide molecules*	*Ratio*		*Ions per 24 anions*	
Si^{4+}	.9990	X 7.99	X 1	7.98	7.98
Mg^{2+}	.6049	"	X 1	4.83	
Fe^{2+}	.0111	"	X 1	0.09	4.93
Mn^{2+}	.0004	"	X 1	0.003	
Li^{1+}	.0003	"	X 2	0.005	
Ca^{2+}	.2389	"	X 1	1.91	
Na^{1+}	.0019	"	X 2	0.03	1.94
K^{1+}	.0002	"	X 2	0.003	
OH^-	.1210	"	X 2	1.93	2.14
F^-	.0263	"	X 1	0.21	

Composition Number = 0, 0, 0, 1oo, 0.03, 1o, 1, 0, 0, 1.79
Name - Tremolite

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