CLAY MINERALOGY AND CLAY PARAGENESIS OF THE
UPPER CHASE AND LOWER SUMNER LIMESTONES
AND SHALES IN NORTH AND EAST CENTRAL KANSAS

by

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INTRODUCTION

Purpose of Investigation

The purpose of this investigation was to determine the clay mineralogy and clay petrology of the limestones and shales of the Upper Wolfcamp Series and Lower Leonard Series of North and East Central Kansas. Very little previous work has been done on the Permian section above the chert bearing limestones of the Barneston formation. The Nolans formation and the lower part of the Wellington formation were used as a base for comparative studies in the present investigation.

A corollary purpose of the present study, in addition to that of clay mineral identification, was to relate certain clay mineral assemblages to the carbonate-quartz mineralogy of the rock. Previous workers have suggested that the clay-carbonate-quartz system possesses various phases of equilibrium in common which can be used to predict physical and chemical changes which have evidently occurred during the depositional history of the rock. A petrographic and petrologic study of the clay minerals found in one formation which has been sampled over a large area should throw additional light on this problem.

In previous work there has been evidence that some associated interstratified clay mineral complexes could reveal diagenetic changes which have taken place. Other clay mineral interstratifications could well serve as criteria for the recognition of the time extent and effectiveness of weathering processes. If these

hypotheses and speculations can be substantiated, clay minerals
and their interlayered complexes could become weathering and
paleohistoric indices for further sedimentation studies.

The present investigation should reveal a possible change
in clay environments and clay mineralogy along the Leonard-Wolf-
camp time-stratigraphic boundary, if the above hypotheses are
valid. It should be possible, therefore, to determine by clay
facies changes the basinal relationships existing during this
segment of Permian time in North and East Central Kansas.

Methods Used

The individual clay minerals and their allied interlayers
were identified by three primary methods: (1) X-ray diffraction
of slides of air-dried oriented clay mineral aggregates, (2) X-
ray diffraction of oriented aggregates treated with ethylene
glycol, and (3) X-ray diffraction of oriented clay mineral aggre-
gates which had been heated to temperatures of 450 degrees Cen-
tigrade and higher.

Techniques of ion saturation were used as a supplementary
method. The carbonate mineralogy was determined by X-ray powder
diffraction methods, and carbonate percentages were calculated
from insoluble residue analysis. From a combination of these
methods, a relatively accurate identification of the clay and
carbonate mineral constituents can be made.

REVIEW OF LITERATURE

Clay Mineralogy

The science of clay mineralogy was basically founded on the
clay mineral concept which came into existence about 1920. Grim
(1953), p. 18, said:

> According to the clay mineral concept, clays are
> essentially composed of extremely small crystalline par-
> ticles of one or more members of a small group of min-
> erals which have come to be known as the clay minerals.
> The clay minerals are essentially hydrous aluminum
> silicates, with magnesium or iron proxying wholly or in
> part for the aluminum in some minerals and with alkalis
> and alkaline-earths present as essential constituents
> in some of them.

Clay minerals are classified into various groups according
to their structure and composition. This classification and
recent modifications to it have been presented by Grim (1953),
p. 27.

The Relationship of Clays to Their
Depositional Environment

The most extensive research in the field of clay mineralogy
during the past decade has been concerned with attempts at estab-
lishing certain clay environmental relationships which may be
used in the future as a stratigraphic tool.

Clays may occur as authigenic (residual) or as allogenic
(transported clay), Ries (1927), pp. 1-10. The residual clays
are formed on the weathered surface of the rock by: (1) the

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decomposition of silicate minerals in the rock, (2) solution of carbonate rocks containing insoluble clayey impurities and subsequent concentration of these impurities, (3) the disintegration and possibly some alteration of shales, (4) hydrothermal solutions, and (5) alteration by meteoric water. Transported or allogenic clays are those that have been transported from their area of formation to a site of deposition.

Voluminous literature has been written about these various sites of deposition and their active and passive effects upon clay minerals. Recently, the greatest controversy to arise over clay mineral alteration is that of the effects of diagenesis versus the cause and effect of ionic adsorption supposed to have taken place in the depositional environment.

Millot (Grim, 1953, p. 351) has presented evidence that the calcium in an alkaline marine environment tends to block or prohibit the formation of kaolinite. This particular environment favors the formation of illite, montmorillonite, and chlorite. Millot also found that illite was invariably present in sediments of marine origin, and that an environment of low cation content is more favorable to kaolinite formation, whereas a higher cation content favors montmorillonite.

Grim (1953) proposed that kaolinite is relatively less abundant in ancient marine sediments and must undergo a change to some other clay mineral. Weaver (1958) stated that kaolinite is most common in continental or near shore sediments; therefore it is probably less abundant in ancient sediments because continental deposits are preferentially destroyed by erosion.

Zen (1959) postulated that calcite and kaolinite seem to be physically and chemically compatible in some Peruvian sediments. These particular sediments have volcanic glass as a primary constituent. Zen implied that the presence of the calcite-kaolinite pair in marine sediments which contained devitrified glass excludes any possibility of an organic or detrital origin for this particular phase. Some of the clay mineral groups can be placed into a seven-component system of phase equilibrium where the oxides are used as end members of a hypothetical solid solution series which may be derived from within the system.

Zen used Gibb's Phase Rule, which related the number of phases, $\emptyset$, with the number of independent components, c, to form the equation, $w = c + 2 - \emptyset$, where w, the variance or degrees of freedom, is the number of independent conditions that must be imposed on a system for its unique description. In order to use CaO, MgO, FeO, and Al_2O_3 as a solid-phase system of four components, SiO_2, CO_2, and H_2O were set aside as mobile components on the assumption that these mobile constituents would be fixed by the environment. The oxides, K_2O and Na_2O, essential in the formation of illite and some montmorillonite respectively, would require the addition of these end members to relate any revisional changes which these oxides would impose upon the general phase relationships of the system. These equilibrium relationships of Zen's are partially illustrated in Plate I.

Grim (1953), p. 356, stated that montmorillonite is generally absent in sediments older than the Mesozoic. Volcanic ash falls in which the devitrification of volcanic ash or glass has

EXPLANATION OF PLATE I

Figures 1 and 2 show possible alternative assemblages in the system Al_2O_3 - CaO - FmO in the presence of quartz and at particular values of temperature, pressure, aH_2O, and a_{CO_2}. After Zen (1959).

These figures are related by the reaction: calcite + chlorite + carbon dioxide = dolomite + kaolinite + quartz + water.

Figures 3, 4, and 5 are schematic representations of the successive phase assemblages that must be obtained to correspond to Figs. 1 and 2.

The reaction from Fig. 3 to Fig. 4 is montmorillonite + calcite + carbon dioxide = kaolinite + dolomite + quartz + albite + water.

The reaction from Fig. 4 to Fig. 5 is montmorillonite + dolomite = calcite + chlorite + albite + quartz + water + carbon dioxide.

formed montmorillonite are responsible for the bentonite found in the Mesozoic sediments. In sediments older than the Mesozoic the montmorillonite has probably changed to some other clay mineral, usually illite, by diagenetic processes (Grim, 1951).

Illite is generally the dominant clay mineral in limestones and dolomites and is thought to be primarily authigenic (Grim, et al., 1937; Millot, 1953). According to Weaver (1958), p. 260, illite in the clay sized fraction is analogous to the abundance of quartz in the sand and silt sized fractions, and therefore has no real connotations as an environmental indicatrix.

Weaver (1958), p. 858, believed that the montmorillonite found in most marine sediments is not pure montmorillonite, but may contain from 10 to 30 per cent 10A ("illite") layers and sometimes chlorite layers. With increased potassium fixation during weathering processes, the water layer in the montmorillonite and the brucite layer of degraded chlorites will experience gradual substitution by potassium, so that the resulting illites will become more pure through geologic time, and consequently richer in K_2O content.

Powers (1957), p. 362, suggested that a chloritic clay was forming from degraded illite and/or montmorillonite apparently through a mixed layer vermiculitic stage in most of the estuarine and marine sediments off the California coast.

Weaver (1958) surmised that: (1) Clay minerals do not originate entirely in their depositional environments, and (2) generally they are not strongly modified by the depositional environment. These two generalities led Weaver to the following

conclusions: (1) No particular clay mineral is restricted to a particular environment; (2) illite, montmorillonite, and inter-stratified illite-montmorillonite can occur in abundance, frequently as the only clay mineral assemblage present in any depositional environment; (3) kaolinite is dominant mainly in fluvatile environments; (4) chlorite is usually a minor but universal constituent in sediments of all environments; and (5) continental shales are rarely monomineralic but contain large amounts of mixed layer assemblages along with the individual clay mineral groups. These clays reflect heterogeneous source and environmental areas.

Mixed-layer Clay Minerals

One of the most unique features of clay minerals is that they commonly occur as interstratifications of two or more component clay minerals possessing similar structural and compositional characteristics. These mixed-layer clays are able to form as random or regular interlayered sequences. Weaver (1956), p. 203, defines a random mixed layer as one which results when two or three different types of layers forming the interlayer occur in a random intergrowth. This type of interlayered clay forms a non-integral stacking sequence in the c direction of the c parameter of the unit cell. Then, by comparison, a regular mixed layering sequence would be one in which two or more different types of layers occur in a regular stacking sequence, i.e., AB, AB, AB, or AAB, AAB, AAB (Bradley, 1950).

Recent literature has compiled a large list of interlayered clay mineral combinations which have been found to exist. Some of the more common types which have been reported are: illite-montmorillonite, illite-chlorite, chlorite-montmorillonite, illite-chlorite-montmorillonite, montmorillonite-vermiculite, and vermiculite-chlorite. A majority of these clay minerals are random. Regular interlayers have been reported but are thought to be rare (Weaver, 1956). One of the earliest regular interlayers to be described was rectorite (Bradley, 1950). Rectorite exhibited an alternating sequence of layers consisting of one pyrophyllite layer and one vermiculite layer per unit cell. Both components contained alumino-silicate layers resembling pyrophyllite with an additional water layer comparable to that of vermiculite.

Lippman (1956) proposed the name corrensite to designate a regular interstratification consisting of chlorite and vermiculite or montmorillonite ("swelling chlorite") coordinated into a 1:1 layer sequence. This "swelling chlorite" from the Triassic beds of Germany is a form of chlorite which has experienced partial destruction and removal of the brucite layer and subsequent addition of water in those places where the brucite sheet has been removed. The removal process has not gone to completion to the extent that a water layer like that of vermiculite and montmorillonite would be produced, but the mineral still has very pronounced expansional properties. Upon heating to temperatures higher than 450 degrees Centigrade, the interstratification or mineral behaves as a chlorite rather than a vermiculite

or montmorillonite. Other regular interstratifications conforming to Lippman's description of corrensite have been reported by Stephen and MacEwan (1951) and Honeyborne (1951).

Illite-montmorillonite commonly occurs as a primary clay mineral constituent in at least 80 per cent of the sedimentary rocks and is usually random (Weaver, 1956). A regular interlayer of illite-montmorillonite was reported to be present in some South African shales by Heystek (1954). Bonorino (1959) identified regularly interstratified illite-montmorillonite as being present in hydrothermally altered veins along the Colorado Front Range, west of Boulder, Colorado. In both of these occurrences, the ratio of the constituents was an alternating 1:1 layer sequence. Weaver (1953) gave the name metabentonite to those random interstratifications composed of 80 per cent illite and 20 per cent montmorillonite.

Weaver (1956) stated that mixed-layer clays are either formed by diagenesis in a basin of deposition or by weathering in situ in the source area. However, it is believed that originally a large part of the mixed-layer illite-montmorillonite and chlorite-montmorillonite clay interlayers are formed by marine diagenesis, whereas mixed-layer chlorite-vermiculite clays, primarily because of their relatively large grain size, are considered to have been formed by weathering processes. Most mixed-layer clays seem to be derived from the degradation or aggradation of pre-existing clay minerals.

Powers (1957) proposed that randomly interlayered vermiculitic clays change to diagenetic chlorite as an adjustment to the

marine environment. The gradual chloritization process is prob-
ably achieved by the precipitation of octahedrally coordinated
magnesium as islands on the basal surfaces of the clays. The
development of the interlayer enhances the chemical and thermal
stability of the chlorite.

The Effects of Weathering on Clay Minerals

The effects of weathering processes on the alteration of
clay mineral constituents in limestones, shales, and soils seem
to be as influential if not more so than the effects produced
by diagenetic processes and sedimentary environments. Grim
(1958), p. 247, postulated that if conditions of climate and
topography do not favor leaching so that the alkalis and alka-
line-earths remain in the weathering zone and are concentrated
there, the clay mineral components favored are illite, mont-
morillonite, and chlorite, according to the prevalence of potas-
sium or magnesium and the concentration of the magnesium. How-
ever, if the leaching does tend to remove the alkalis and alka-
line-earths, the clay mineral will generally be kaolinite.
Frederickson (1952) and Griffiths (1952) generally regarded
kaolinite as an end product of weathering.

According to Keller (1958), p. 242, a relatively high con-
centration of metallic ions and silicate ions tend to form mont-
morillonite, illite, and other 2:1 layer clays. Geologic factors
leading to this condition are: (1) Parent rock rich in Ca^{++},
Mg^{++}, Fe^{++}, with or without K^+ and Na^+; (2) volcanic glass;

(3) semi-arid climate; (4) stagnant water in humid climate; (5) flocculation of SiO_2 by multi-valent cations; and (6) pH of the weather system not less than neutral. A slight depletion of alkalis and magnesium during the interval of weathering of a Pennsylvanian disconformity reflected the destruction of the chlorite and alkali removal by leaching processes (Dalton, Swineford, and Jewett, 1956, p. 251).

Milne and Earley (1958), p. 328, suggested that montmorillonite, the predominant clay mineral in the Mississippi River and associated delta deposits, is apparently the stable product of soil development and rock weathering in the drainage basin of the Mississippi River. Murray and Leininger (1955), p. 347, believed that the initiating mechanism for the change from chlorite and illite to montmorillonite is the oxidation of ferrous iron in the octahedral layer. When these weathered clays are eroded and transported by streams and subsequently carried back into the marine environment, they will revert back to their original types: illite and chlorite. A similar statement can be made for diagenetic clays that have been changed during weathering in that they will also revert back to their original types because their basic skeletal structures still persist. These structures accommodate ferrous ions of iron, magnesium, and/or hydroxyl ions when available in the marine environment. Powers (1957), p. 359, found that random mixed-layer stacking arrangement appears to have resulted from ion exchange and differential hydration of the weathered clays coupled with a regeneration of some of the weathered or degraded clays.

The illite and chlorite in some of the Pennsylvanian shales examined by Harrison and Murray (1957), p. 144, have progressively altered under the influence of weathering by formation of expandable layers within the crystallites, resulting in a mixed-layer structure. The mechanism by which the illite and chlorite are changed to mixed-layer clay containing these expandable layers is either oxidation of iron in the octahedral layers or the replacement of potassium in illite by the hydronium ion. Rich (1956) found that muscovite-type micas weather to form di-octahedral vermiculite which is accomplished by the expansion of the mica structure and subsequent loss of potassium. Studies on New England soils by Tamura (1955), p. 413, showed that possibly the weathering of interstratified vermiculite-illite could result in the formation of alumina in interlayer positions.

AREA OF INVESTIGATION AND FIELD PROCEDURE

The Permian limestones, dolomites, and shales used in this investigation were collected from the Upper Chase Group and Lower Sumner Group at outcrop locations in North and East Central Kansas. The areal locations and stratigraphic positions of the quarry sites and roadcuts from which sampling was done are listed in Table 1. An index map showing the exact location of the sampling sites is given in Fig. 1 of the Appendix.

All of the sampling was of the "spot" type. Krumbein and Pettyjohn (1938) define this as sampling at isolated spots at particular points within an outcrop. This is the best method of

EXPLANATION OF PLATE II

A map showing the area of Kansas which was
sampled in this investigation.

PLATE II
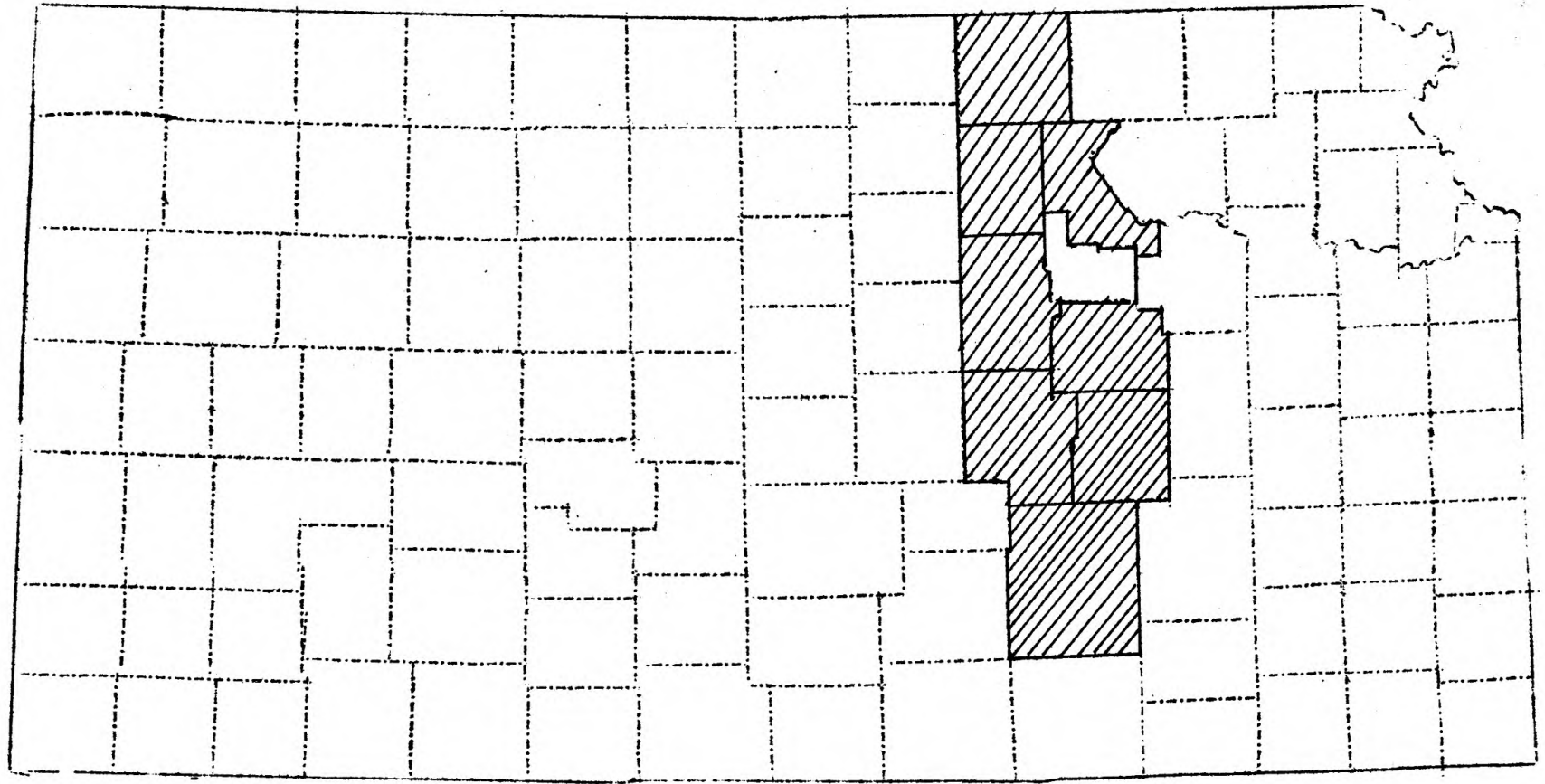
scale

0   20   40
Miles

Table 1.   Location of Permian rocks sampled in this investigation.

Sample number	Formation	Member	Land description	County
	LEONARD SERIES - SUMNER GROUP			
WSWe 2	Wellington	-	SW 1/4,Sec.16,T2S,R4E	Washington
CYWe 1-6-7	Wellington	-	SEc,Sec.31,T9S,R3E	Clay
WSHbl-1	Wellington	Hollenberg	SW 1/4,Sec.16,T2S,R4E	Washington
RLHb 1	Wellington	Hollenberg	CW line,Sec.1,T6S,R4E	Riley
CYHb 1-4-5	Wellington	Hollenberg	SEc,Sec.31,T93,R3E	Clay
CYHb 2	Wellington	Hollenberg	SW 1/4,Sec.8,T91S,R3E	Clay
DKHb 1	Wellington	Hollenberg	SW 1/4c,Sec.19,T11S,R3E	Dickinson
DKHb 2	Wellington	Hollenberg	SE1/4,Sec.5,T14S,R4E	Dickinson
MRHb 1	Wellington	Hollenberg	CS line,Sec.21,T17S,R5E	Morris
CHHb 1	Wellington	Hollenberg	NW line,Sec.3,T22S,R6E	Chase
WSWe 1	Wellington	Pearl	NW 1/4,Sec.16,T2S,R4E	Washington
RLWe 1	Wellington	Pearl	CW line,Sec.1,T6S,R4E	Riley
CYWe 1	Wellington	Pearl	SEc,Sec.31,T9S,R3E	Clay
CYWe 2	Wellington	Pearl	SEc,Sec.30,T10S,R3E	Clay
DKWe 1	Wellington	Pearl	NE 1/4,Sec.30,T11S,R3E	Dickinson
DKWe 2	Wellington	Pearl	SE 1/4,Sec.5,T14S,R4E	Dickinson
MRWe 1	Wellington	Pearl	CS line,Sec.21,T17S,R5E	Morris
CHWe 1	Wellington	Pearl	NW 1/4,Sec.3,T22S,R6E	Chase
	WOLFCAMP SERIES - CHASE GROUP			
WSHe 1	Nolans	Herington	NW 1/4,Sec.16,T2S,R4E	Washington
RLHe 1	Nolans	Herington	SW 1/4,Sec.13,T7S,R5E	Riley
RLHe 2	Nolans	Herington	SE 1/4c,Sec.36,T7S,R5E	Riley
DKHe 2	Nolans	Herington	NE 1/4,Sec.30,T11S,R3E	Dickinson
DKHe 1	Nolans	Herington	S line,Sec.4,T12S,R3E	Dickinson
MRHe 1	Nolans	Herington	CS line,Sec.13,T15S,R5E	Morris
MRHe 2	Nolans	Herington	NW 1/4,Sec.31,T15S,R5E	Morris
CHHe 1	Nolans	Herington	NE 1/4,Sec.28,T21S,R6E	Chase
MNHe 1	Nolans	Herington	SW 1/4,Sec.26,T18S,R4E	Marion
WSPa 1	Nolans	Paddock	NW 1/4,Sec.16,T2S,R4E	Washington
RLPa 1	Nolans	Paddock	SW 1/4c,Sec.13,T7S,R5E	Riley
RLPa 2	Nolans	Paddock	SE 1/4c,Sec.36,T7S,R5E	Riley
RLPa 3	Nolans	Paddock	SE 1/4,Sec.25,T7S,R4E	Riley
DKPa 1	Nolans	Paddock	S line,Sec.4,T12S,R3E	Dickinson
MRPa 1	Nolans	Paddock	CS line,Sec.13,T15S,R5E	Morris
MRPa 2	Nolans	Paddock	NW 1/4,Sec.31,T15S,R5E	Morris
CHPa 1	Nolans	Paddock	NE 1/4,Sec.28,T21S,R6E	Chase
MNPa 1	Nolans	Paddock	SW 1/4,Sec.26,T18S,R4E	Marion

Table 1 (Concl.).

Sample number	Formation	Member	Land description	County
RLKr 1	Nolans	Krider	SE 1/4,Sec.25,T7S,R4E	Riley
MRKr 1	Nolans	Krider	NW 1/4,Sec.31,T15S,R5E	Morris
RLOd 1	Odell	-	SE 1/4,Sec.25,T7S,R4E	Riley
DKOd 1	Odell	-	NWc,Sec.2,T16S,R4E	Dickinson
MROd 1	Odell	-	NW 1/4,Sec.14,T15S,R6E	Morris
RLCr 1	Winfield	Cresswell	CN line,Sec.1,T9S,R4E	Riley
DKCr 1	Winfield	Cresswell	SE 1/4,Sec.1,T12S,R3E	Dickinson
DKCr 2	Winfield	Cresswell	SE 1/4,Sec.35,T15S,R4E	Dickinson
RLGr 1	Winfield	Grant	CN line,Sec.1,T9S,R4E	Riley
DKGr 1	Winfield	Grant	SE 1/4,Sec.1,T12S,R3E	Dickinson
DKGr 2	Winfield	Grant	SE 1/4,Sec.35,T15S,R4E	Dickinson
BUGr 1	Winfield	Grant	CS line,Sec.28,T26S,R4E	Butler
RLSt 1	Winfield	Stovall	CN line,Sec.1,T9S,R4E	Riley
DKSt 1	Winfield	Stovall	SE 1/4,Sec.1,T12S,R3E	Dickinson
CHSt 1	Winfield	Stovall	CS line,Sec.8,T21S,R6E	Chase
RLGg 1	Doyle	Gage	NW 1/4,Sec.20,T7S,R5E	Riley
RLGg 2	Doyle	Gage	CN line,Sec.1,T9S,R4E	Riley
DKGg 1	Doyle	Gage	SE 1/4,Sec.1,T12S,R3E	Dickinson
CHGg 1	Doyle	Gage	CS line,Sec.8,T21S,R6E	Chase
BUGg 1	Doyle	Gage	CS line,Sec.28,T26S,R4E	Butler
RLTo 1	Doyle	Towanda	C,Sec.17,T9S,R5E	Riley
CHTo 1	Doyle	Towanda	NW 1/4,Sec.23,T21S,R6E	Chase
BUTo 1	Doyle	Towanda	NW 1/4,Sec.9,T26S,R4E	Butler
BUTo 2	Doyle	Towanda	NE 1/4,Sec.4,T27S,R4E	Butler
RLHv 1	Doyle	Holmesville	C,Sec.17,T9S,R5E	Riley
CHHv 1	Doyle	Holmesville	CE line,Sec.19,T22S,R7E	Chase
CHHv 2	Doyle	Holmesville	NW 1/4,Sec.23,T21S,R6E	Chase
BUHv 1	Doyle	Holmesville	NW 1/4,Sec.9,T26S,R4E	Butler
BUHv 2	Doyle	Holmesville	NE 1/4,Sec.4,T27S,R4E	Butler
CHFr 1	Barneston	Fort Riley	CE line,Sec.19,T22S,R7E	Chase
CHFr 2	Barneston	Fort Riley	NW 1/4,Sec.23,T21S,R6E	Chase

checking the clay mineral composition within a single rock unit.
Care was taken to see that the weathered rock was not incorpor-
ated in the unweathered material and the reverse. Wherever pos-
sible, weathered and unweathered samples from a particular
stratigraphic unit were collected from within the same general
area. By this method of duplication, a weathering index could
be made to compare the effects weathering processes have had on
changes in clay mineral composition. The Herington and Paddock
members of the Nolans limestone formation and the Hollenberg mem-
ber and Pearl shale member of the Wellington formation were sam-
pled along two north-south lines. This sampling distribution
was done to study the changes in clay mineralogy three-dimen-
sionally, i.e., north-south, east-west, and vertically.

The number of samples taken at a given outcrop was control-
led by the number of lithologic changes occurring in the unit as
observed in the field. Where no visible lithologic break was
encountered in rock units of greater than three feet in thick-
ness, samples were collected from the top, middle, and bottom of
the unit. Each sample was placed in a sample sack and was
labeled as to geographical location and stratigraphic horizon.
A detailed lithologic description of each unit, including
measured thickness, was then recorded in a field book. The
measured sections and the lithologic descriptions are listed in
the Appendix. Each sample was given a code number to designate
county, number of outcrop, and number of sample within the out-
crop in ascending order as it was taken. The standard Kansas
county abbreviations were used for county identification. For

example, RLPa 3-1 would signify that the sample was the bottom-most unit collected from the third section of Paddock shale sampled in Riley County. The number of the particular sample occurring last in the code holds no correlative connotations with a corresponding number of the same formation from another location. A stratigraphic cross section showing the stratigraphic relationships of all samples collected is illustrated in Fig. 2 in the Appendix.

LABORATORY PROCEDURE

Preparation of Clay-sized Materials

The procedure used for the preparation of the clay-sized material for X-ray analysis was essentially the same as that described by Asmussen (1958), p. 12. Asmussen stated that hydrochloric acid was not used to remove the carbonates in the limestones because the acid often destroys chlorites and certain types of montmorillonites during the process of carbonate removal. The author found that carbonate rich clay suspensions could be safely leached by either 1:1 cold hydrochloric acid or concentrated acetic acid without any evident destruction of the chlorite and montmorillonite. These suspensions were concentrated where the sample had less than 10 per cent insoluble residue. Mere concentration by volume of clay suspension per volume of water did not give the desired quality of X-ray diffraction pattern because the colloidal calcite, dolomite, goethite, and

quartz often caused disorientation of the clay mineral flakes
from the preferred basal pinacoid orientation.

X-ray Analysis

The X-ray unit is divided into three separate parts: water
cooler, North American Phillips diffraction unit, and North
American Phillips electronic circuit panel. The diffraction
unit is equipped with both cameras and geiger counter goniometer.
The goniometer permits the use of both powder and oriented slides.
Clay identification was done by the oriented slide method and
the carbonate minerals were determined by the powder method.
The slides were exposed to nickel-filtered copper radiation, us-
ing 20 milliamperes and 40 kilovolts with a one-degree solar slit
system. The scanning speed of the goniometer was one-fourth de-
gree two theta per minute. The goniometer was traversed through
an angle of 32 degrees to two degrees two theta for untreated
slides, and 15 degrees to two degrees two theta for most of the
ethylene glycol and heat-treated slides. Powder diffraction
patterns for the carbonates were traversed through an interval
of 33 degrees to 20 degrees two theta. This interval encom-
passes the strongest reflections for the carbonates, goethite,
and quartz.

Ethylene glycol (CH_2OHCH_2OH) forms an organic complex with
the clays, and with its application the expanding clay minerals,
montmorillonite and "swelling chlorites and vermiculites" can be
identified.

The diffraction angles were read directly from the chart graph paper in degrees two theta. These degrees were then converted to angstron units of the d-spacings of the reflection. Conversions were made by the use of the "Tables for Conversion of X-ray Diffraction Angles to Interplanar Spacings", published by the U.S. Department of Commerce National Bureau of Standards, Applied Mathematics Series 10.

Differential Thermal Analysis

The furnace of the differential thermal apparatus was used as a means of heating slides for further X-ray identification of the clay minerals. The slides were heated at 450 degrees Centigrade from 45 minutes, and then at higher temperatures of 520, 550, 620, and 700 degrees Centigrade for one-half hour when clay mineral identification was still uncertain by X-ray diffraction techniques.

Ion Exchange

Several of the samples containing montmorillonite, vermiculite, and mixed-layer clays with expanding components were treated with different saturated chloride solutions. Saturated solutions of $AlCl_3$, $BaCl_2$, and $MgCl_2$ were added separately to a small portion of the clay suspension. The suspension was then stirred at 30-minute intervals while allowing to stand for three hours. The suspensions were washed by centrifuging several times in

order to remove excess chloride. After four or five washings, a part of the liquid was decanted into a separate beaker and treated with a .12N solution of $AgNO_3$. If no precipitate of $AgCl$ formed, the treated clay was resuspended and oriented slides made for further X-ray analysis.

Samples thought to contain the clay mineral vermiculite were specially treated with a saturated solution of NH_4Cl. The clay suspension containing the ammonium chloride solution was transferred to a beaker and heated at the boiling point of the liquid for five minutes. After washing thoroughly, slides were made for X-ray analysis. The application of NH_4Cl will cause a collapse of the basal spacing to from 14A to 10.5011A if the mineral is vermiculite (Weaver, 1958). The results of X-ray analysis made on slides treated in this manner were inconclusive because the vermiculite was apparently randomly interstratified with chlorite, the latter remaining unaffected by the treatment. The resulting basal spacing depends on the amount of chlorite present more than it does on the relative abundance of vermiculite.

Several samples containing interlayered clay minerals were allowed to stand in concentrated hydrochloric acid for 24 hours. This is one method of determining how much of the interlayering is due to chlorite as it is acid soluble. Two samples having large percentages of montmorillonite were treated with 1N solutions of KOH. Weaver (1958) treated several samples with KOH and believed it possible to differentiate between montmorillonite formed from pre-existing illites and those formed as a by-product

of volcanic ash devitrification. The K-saturated specimen, if
of illitic derivation,should adsorb potassium and collapse to a
basal spacing of 10A, whereas the montmorillonite of volcanic
origin is not affected. The illite derived montmorillonite was
then treated with a 1N solution of $CaCl_2$ and a re-expansion to
16.6A was observed. Both of these treatments require the sample
to stand in solution for 15 hours. The results of some of these
tests will be discussed in a later section.

Insoluble Residue Determination

Insoluble residue percentages were calculated on all of the
carbonate rocks and some of the shales. Only those shales show-
ing appreciable amounts of carbonate minerals were used. Two
hundred grams of crushed oven-dried rock material which was not
used in the X-ray diffraction studies were employed for the in-
soluble residue studies. The general procedure followed by the
author was the same as that outlined by Hargadine (1959), p. 21.
In this investigation the color of the filtrate resulting from
the washing procedure in the Buechner funnel was recorded. The
color was thought to be an approximate indication of the rela-
tive amount of soluble iron present in the sample.

INTERPRETATION OF X-RAY DATA

Clay Mineral Determination

Literature devoted to the discussion of clay mineral identi-
fication by X-ray diffraction techniques has resulted in the
compilation of many different clay mineral names. Some of these
particular designations apparently apply to the same mineral
which has been separately described by different authors. For
instance, vermiculite (Weaver, 1956), montmorillonite (Earley,
et al., 1956), and swelling chlorite (Alietti, 1958) all have
reportedly the same X-ray reflectional characteristics but have
been assigned a different clay mineral name by each author. The
purpose of the following discussion is to present the nomencla-
ture to be used by this author in outlining the criteria used to
distinguish between specific clay minerals and between their
interlayer complexes.

Illite was recognized by its fundamental periodicity of 10A.
The basal series of reflections for the first three orders are
10A, 5A, and 3.33A, respectively. The illites were placed into
one of three groups, depending upon the peak character and the
basal reflection intensity ratios. No expansion occurs within
the layers of illite, and consequently it is not affected by the
ethylene glycol treatment. Reference to Plate III shows the
different classes of illite.

Class 1. Peak reflections are sharp and the intensity of
the first order reflection is larger than that of the third order

and is usually three to five times larger than the intensity of the second order. This type of illite is evidently well crystalline.

Class 2. All basal reflections are broader than those of Class 1 and the peak apices are always blunted; however, the relative intensity ratios between reflections are approximately of the same magnitude as those of Class 1. Reflections are often separated into doublets. These illites are evidently degraded in which certain crystal imperfections and lattice vacancies have been reflected in the breadth of the peak and they represent poorer crystallinity than Class 1.

Class 3. The (002) reflection is weak and often diffuse, indicating the presence of iron as a substitutional atom in the octahedral layer (Weaver, 1958). This type is closely related to the other two classes with reference to other basal peak configurations.

Montmorillonite has a fundamental spacing of 14A which expands to a spacing of 17-17.5A upon the application of ethylene glycol. Higher order reflections are usually absent unless the mineral is present as a major constituent of the clay fraction. The (002) reflection occasionally appears at 8.5A. Upon heating to 450 degrees Centigrade, montmorillonite loses its water layer and collapses to 10A to become an additive phase of the (001) reflection of illite. For this text, the name montmorillonite will be reserved for the clay mineral whose peak disappears at 450 degrees Centigrade and whose basal planes reflect expansion after glycolation.

EXPLANATION OF PLATE III

X-ray diffractometer smooth tracings of the classes of illite.

Fig. A. Class 2 illite pattern showing the broad peak terminations. This type of illite is degraded or poorly crystalline.

Fig. B. Class 3 illite, exhibits broad peaks and a weak (002) reflection. This type shows poorly crystalline iron-rich illite where the peak ratio is around .12. Class 3 illite can be placed in with Class 1 or Class 2, depending upon the peak acicularity.

Fig. C. Class 1 illite exhibits sharp peak terminations, denoting good crystallinity and a sub-curve areal peak ratio of greater than .2.

PLATE III
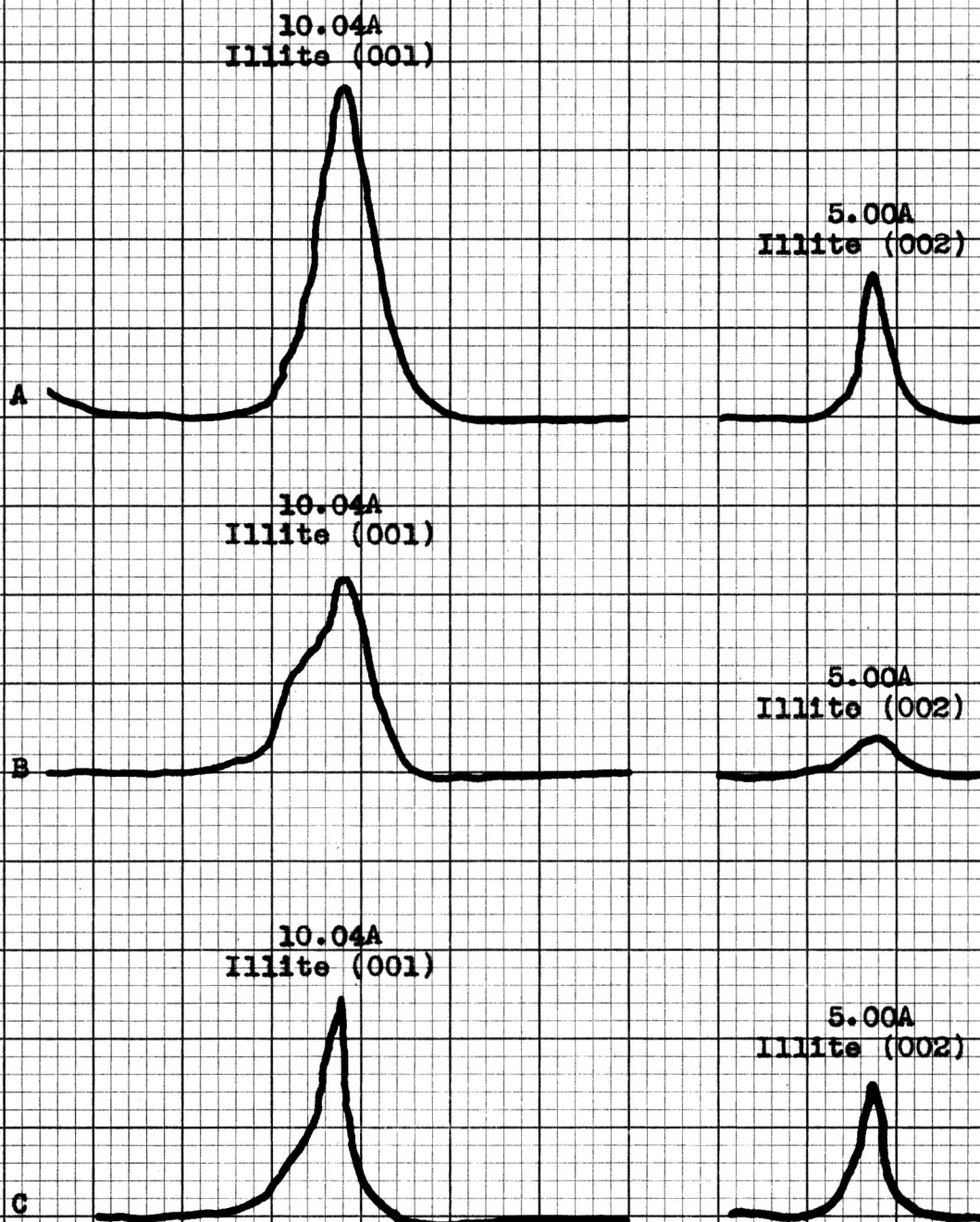
Chlorite. Eight varieties of 14A chlorite were identified
and grouped according to their behavior toward the effect of
heat treatments at 450, 550, 620, and 700 degrees Centigrade.
Untreated slides were X-rayed through 32 degrees two theta to
include the first five basal reflections while patterns of the
heat-treated slides encompass the first two basal reflections.

Class 1. When heated to 450 degrees Centigrade for 45 min-
utes and air quenched, the 14A peak disappears and the 7A peak
does not change, which indicates that the 7A reflection is due
solely to kaolinite (Schultz, 1958). Higher order basal reflec-
tions are absent, and hence this variety conforms to the de-
scription of vermiculite (Plate IV).

Class 2. When heated to 450 degrees Centigrade, the 7A
peak disappears. This variety of chlorite rarely gives a 14A
reflection and when it does, the 14A peak is very weak in com-
parison to the (002) reflection at 7A. This type has strong,
even reflections and weak or absent odd reflections. This
variety was designated as iron rich poorly crystalline since
the presence of iron in vacant octahedral sites often changes
the chlorite structure and polarization factors for the odd order
reflections, and in most cases cancels out the reflection en-
tirely (Plate IV).

Class 3. All reflections are of equal intensity and, like
Class 2, disappear at 450 degrees Centigrade. This probably
represents iron-free poorly crystalline chlorite (Plate IV).

Class 4. The 14A peak disappears and the decrease in the
7A peak height is usually less than the height of the original

EXPLANATION OF PLATE IV

Fig. A.   Class 3 chlorite where all basal chlorite reflections are of approximately the same intensity. This type is iron-free.

Fig. B.   Class 2 chlorite where even basal reflections are stronger than the odd reflections.   This type is generally iron-rich.

Fig. C.   Class 1 chlorite or vermiculite where the first order reflection is much stronger than successive higher orders.   This variety rarely gives a (002) reflection.

Fig. D.   Tracing of a pattern of a sample heated to 450 degrees Centigrade which describes the behavior upon heating of all of the classes of chlorite mentioned above.

PLATE IV
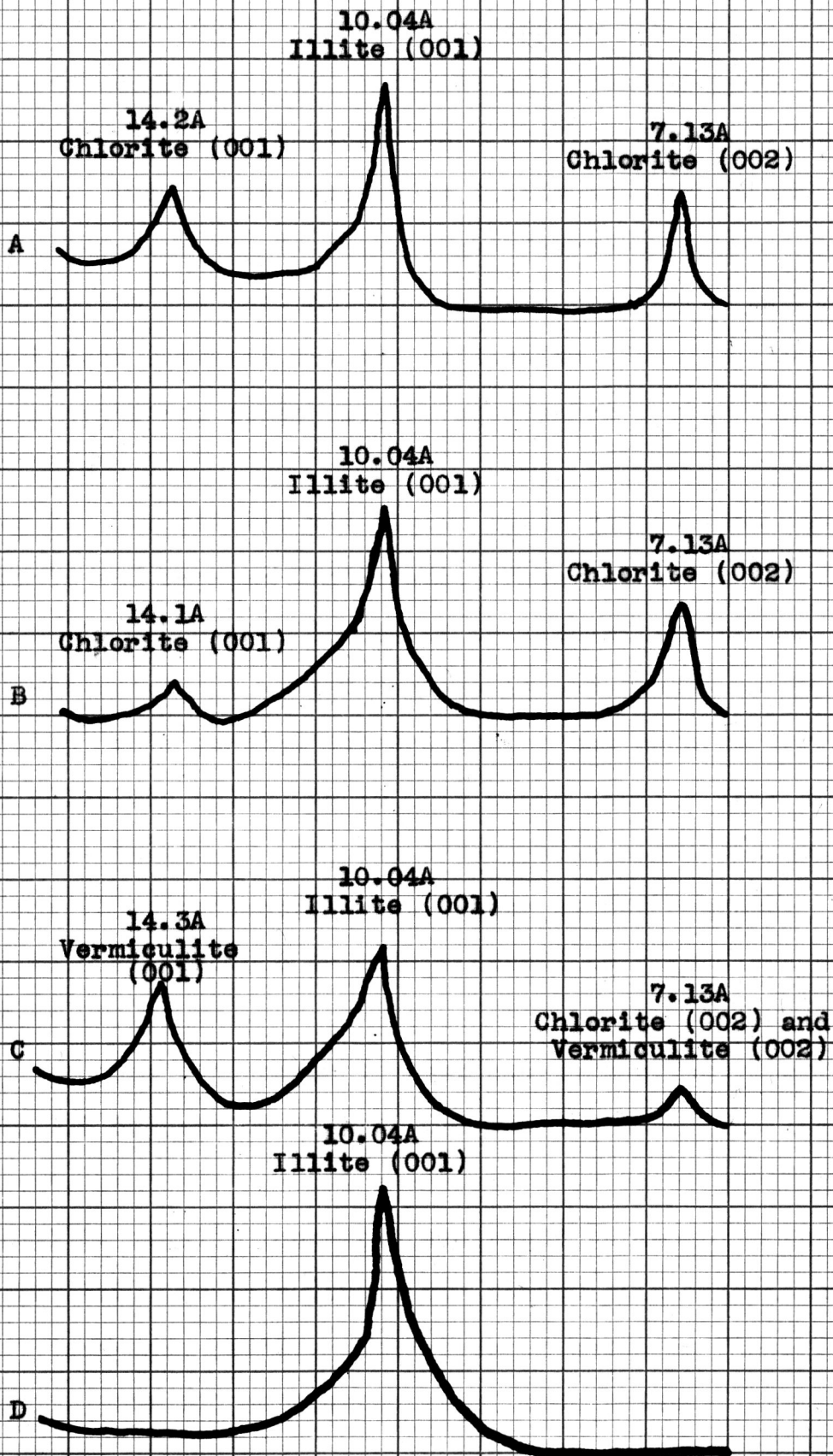
14A peak (Schultz, 1958). This might represent a transitional stage between vermiculite and chlorite and would suggest that the influencing trend is toward a vermiculitic clay. (Plate V).

Class 5. The 14A reflection is little changed at 450 degrees Centigrade and the 7A peak height decreases approximately the height of the 14A reflection. Further heating to 550 degrees Centigrade enhances the 14A reflection (Schultz, 1958). Here the transitional stage closely approaches a chloritic clay mineral. (Plate V).

Class 6. The 14A and all higher order reflections remain unaffected at 450 degrees Centigrade. When heated to 550 degrees, the 14A peak is enhanced. The shift in intensities of the basal peaks by heat treatment at 550 degrees is attributed by Brindley and Ali (1950) to a partial dehydration of the brucite layer. Iron-rich chlorites belonging to this group usually show a decrease in peak height of the even order reflections and occasionally the (001) reflection will appear at 550 degrees. These chlorites were all grouped as well crystalline regardless of the iron content (Plate VI).

Class 7. The 14A and/or 7A peak remain unaffected after heating to 620 degrees Centigrade and 700 degrees. The 14A peak, when present, exhibits partial collapse to 13.8A at 620 degrees. This variety is usually iron-free and seems to approach the thermal stability limits reported for metamorphic chlorites by Turner and Verhoogen (1951). This type is shown in Plate VI.

Class 8. The 14A reflection is of much greater intensity than all of the higher order reflections which are generally

EXPLANATION OF PLATE V

X-ray diffractometer smooth tracings of various
chlorite patterns.

Fig. A. Untreated sample of Class 4 chlorite where
the transformation is from chlorite toward vermiculite.

Fig. B. Same sample heated to 450 degrees Centi-
grade showing disappearance of the (001) and depression
of the (002).

Fig. C. Untreated sample of Class 5 chlorite
where the chloritic characteristics of the mineral
dominate of vermiculitic.

Fig. D. Same sample heated to 450 degrees Centi-
grade.

Fig. E. Same sample heated further to 550 degrees
Centigrade showing the enhancement of the (001) reflec-
tion, near destruction of the (002), and slight col-
lapse of the (001) to 13.85A, denoting a partial loss
of the brucite sheet of the chlorite.

PLATE V
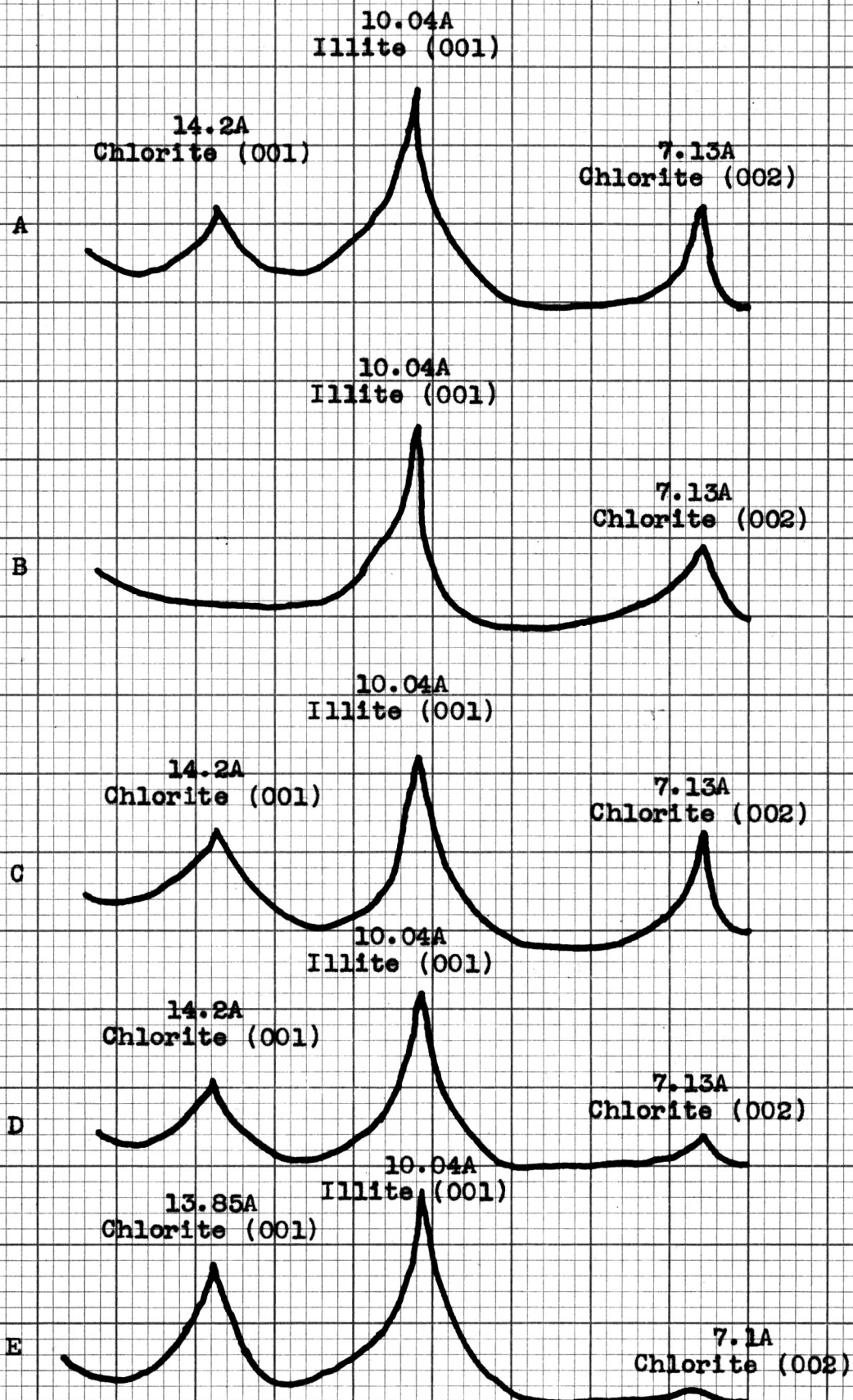
EXPLANATION OF PLATE VI

X-ray diffractometer smooth tracings of chlorite patterns.

Fig. A. Untreated sample of well crystalline Class 6 chlorite.

Fig. B. Same sample heated to 450 degrees Centigrade.

Fig. C. Same sample heated to 550 degrees Centigrade. Notice the increase in intensity of the 14.2A peak.

Fig. D. Untreated sample of very well crystalline Class 7 chlorite which has some of the properties of metamorphic chlorite.

Fig. E. Heated sample to 620 degrees Centigrade where there has been an increase in the (001) reflection and a proportional decrease in the 7.13A (002) reflection.

PLATE VI

A — 14.2A Chlorite (001) ... 7.13A Chlorite (002)

B — 10.04A Illite (001) ... 14.2A Chlorite (001) ... 7.13A Chlorite (002)

C — 14.2A Chlorite (001) ... 7.13A Chlorite (002)

D — 14.2A Chlorite (001) ... 7.13A Chlorite (002)

E — 13.8A Chlorite (001) ... 7.13A Chlorite (002)
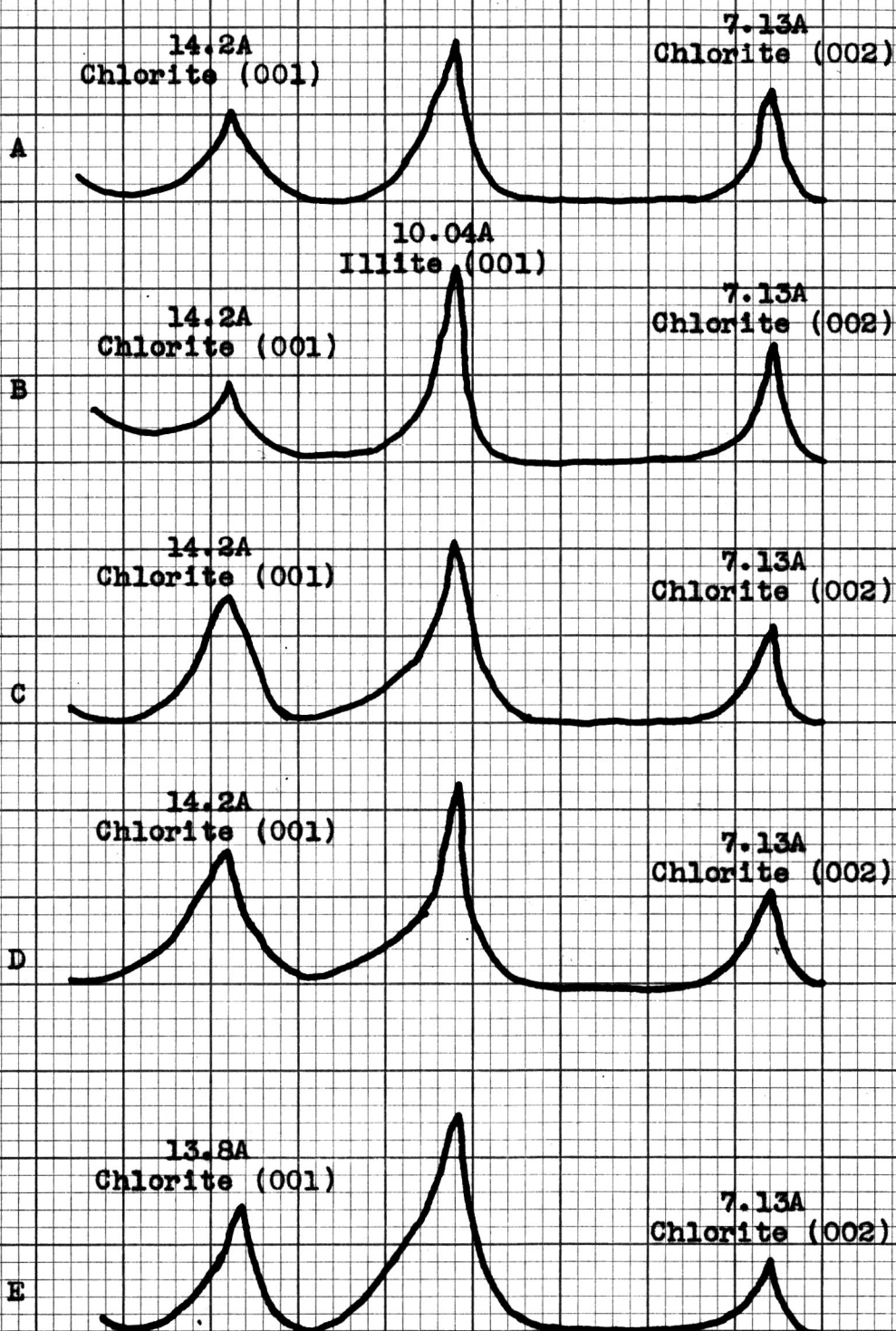
weak or absent. When treated with ethylene glycol and expanded
spacing of 17A results for the (001) reflection. Heating to
450 degrees results in the retention of the 13.8-14A peak which
is further enhanced at 550 degrees. The presence of the 14A peak
at higher temperatures than 550 degrees depends upon the state
of crystallinity of the chlorite. These properties conform to
Lippman's general description of a swelling chlorite. Neither
montmorillonite nor vermiculite resists temperatures above 450
degrees without collapsing to 10A. However, Brown (1954) stated
that a large amount of interlayer organic material prohibits
complete collapse of the vermiculite lattice when heated at tem-
peratures around 400-450 degrees.

Most of the samples studied in the course of this investi-
gation contain one or more varieties of random intergrowth of
two or more clay mineral groups. A few samples from two locali-
ties possessed regular mixed layers. The random interlayers
were recognized as those which gave average reflections situated
between the normal peak positions of the interlayer components.
These peaks represent an average reflection with the exact peak
position depending upon the relative amount of each component
present in the interlayer. A peak at 11A would result from the
average thickness produced by 14A montmorillonite and 10A illite.
A non-integral basal series of reflections is produced by this
type of interlayer.

A regular interlayer will give a (001) value which is equal
to the total thickness of the two or more types of layers which
are present. The regular mixed-layer clays are differentiated

from random mixed-layer clays in that the basal series occurs as
an integral sequence. For instance, a regular mixed-layer il-
lite (10A) and montmorillonite (14A) would give a (001) value
of 24A.

Illite-montmorillonite. The presence of this random inter-
stratification was determined from the asymmetrical configura-
tion which its presence imposes on the low angle side of the 10A
illite reflection and by a similar asymmetric relationship given
to the high angle side of the 3.33A peak of illite. When treated
with ethylene glycol, the (001)/(001) average reflection of the
interlayered material moves from its original peak position to
another position of lower angle, the exact position depending
upon the relative percentages of expanded montmorillonite layers
in the intergrowth. Brown and MacEwan (1950) have published
curves from which these ratios of expanded layers to peak posi-
tion can be read. Heating to 450 degrees will collapse all in-
terlayer components to 10A.

Montmorillonite-chlorite. This interstratification occur-
red as both random and regular interlayer stacking sequences.
Where a distinct integral basal series of reflections was noted,
the clay complex was designated as regularly interstratified.
In this type, the 14A reflections of chlorite and montmorillon-
ite add to give a first order reflection at 28-29A. All higher
orders were recognized as an integrated function of the 28A peak.
However, when the interlayered components were randomly stacked,
the 28A peak was missing since the average (001)M/(001)C reflec-
tion would occur at 14A for the untreated samples. Upon

treatment with ethylene glycol, the 28A reflection shifts to 31A in the case of the regular mixed layer. The 3A increase was attributed to the characteristic 17A first order reflection of montmorillonite after glycolation. Three general groups of montmorillonite-chlorite interstratifications were identified. The author used the same criteria for chlorite differentiation in the interlayer as was done for the individual chlorite species. The groups are shown in Plates VII, VIII, and IX.

Class 1. When glycolated, the 14.4A peak expands toward 17A and heating to 450 degrees evidently destroys the interlayer structure. The untreated 14.4A reflection gives the strongest peak with other basal reflections absent. This type would be an interlayer of montmorillonite and Class 1 chlorite (vermiculite).

Class 2. In this regular interlayer the (001) reflection is at 29A and is weak to diffuse. The second order appears at 14.2A and is the strongest reflection with successive even order reflections becoming progressively weaker with increase in order. The odd orders are essentially absent except for the first and third order reflections. Upon glycolation, the second order reflection shifts to a position of higher spacing in the 14.2-17.3A range, depending upon the proportion of interlayered montmorillonite. When the interlayer is regular, the (002) reflection has a nearly constant spacing at 15.77A relating the 1:1 stacking arrangement of the 8.6A reflection of montmorillonite and the 7.1A reflection of chlorite. Heating to 450 degrees Centigrade depresses the (001) reflection of the regular interlayer to about 24A and the (002) to around 12A. This heating behavior

EXPLANATION OF PLATE VII

X-ray diffractometer smooth line tracings of a portion of a pattern of sample CYWe2-5 of the Wellington shale from southern Clay County, Kansas.

Fig. A. Untreated sample showing a nearly regular series of basal reflections as a function of the 28A first order reflection of a montmorillonite-chlorite interlayer.

Fig. B. After glycolation, the 28A peak has increased in spacing to a doublet of 31.5A and 33.95A, indicating the possibility of two phases in the superlattice structure. The 33.95A reflection is not supported by higher order reflections. This latter reflection represents montmorillonite swelling vermiculite.

Fig. C. Heating to 450 degrees Centigrade records collapse of the 31.5A peak to 23.3A. Notice that the 7.1A peak of chlorite has disappeared.

Fig. D. Further heating to 550 degrees Centigrade continues the collapse of the interlayer spacing to 11.8A, placing this chlorite in Class 5 or higher.

PLATE VII

A — 28.4A, 14.4A, 11.27A, 10.04A, 9.11A Mont-chlor (003), 7.13A Mont-chlorite (004), Chlorite (002)

B — 33.95A, 31.5A Superlattice(001) Mont-verm-chlorite, 15.77A Mont-chlor(002) (1:1), Ill-chlor 001/001, 11.27A, 10.04A Illite(001), 7.92A Mont-chlor(004), 7.13A Chlorite (002)

C — 23.3A Super-lattice (001), 12.44A Mont-chlor(002), 10.04A, 8.42A Mont-chlor(003)

D — 20.5A Superlattice(001), Mont-chlor(002), 10.04A Illite(001)
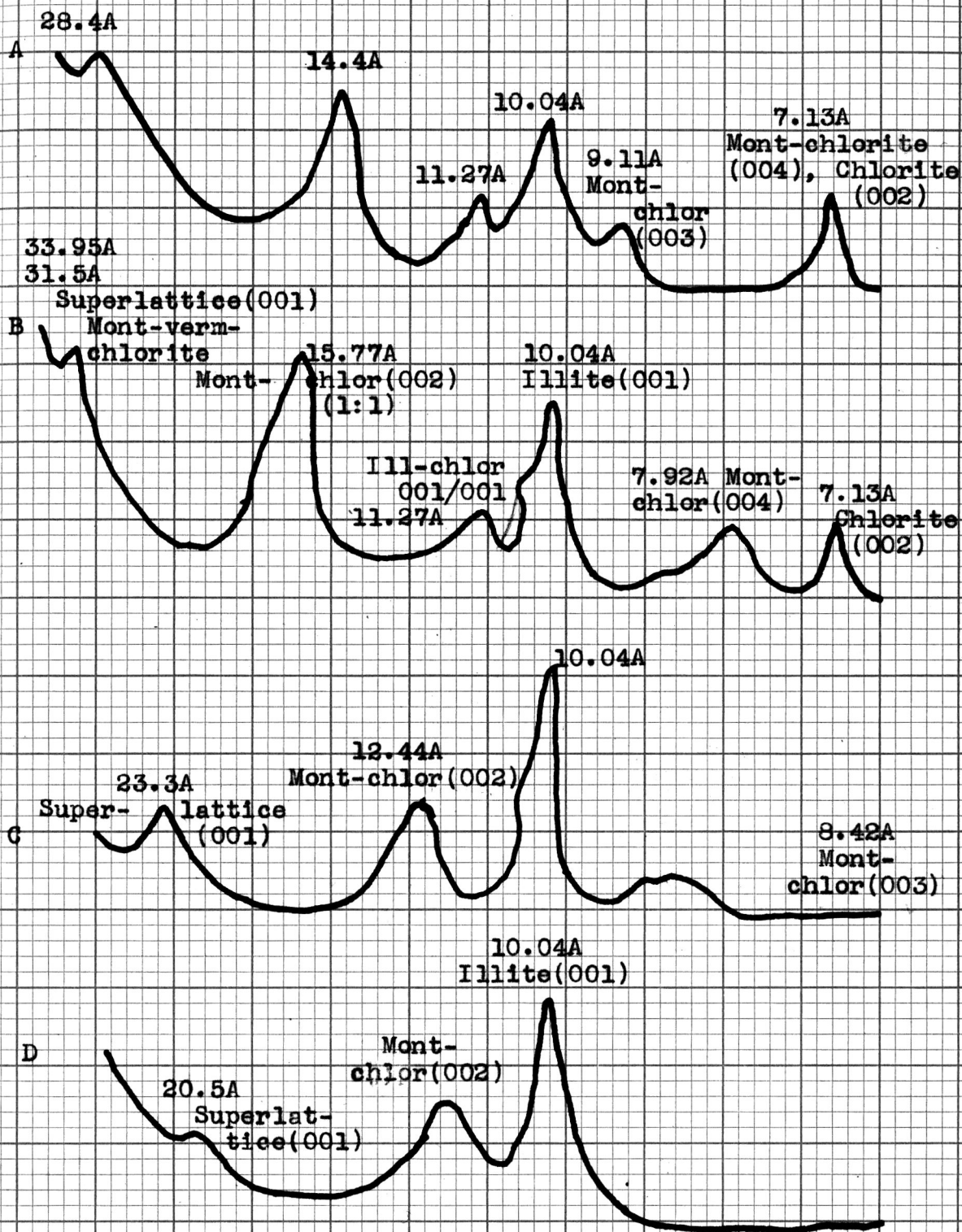
EXPLANATION OF PLATE VIII

X-ray diffractometer smooth tracings of a regu-
larly interlayered montmorillonite-swelling chlorite.
This pattern is similar to the sample of Paddock shale
from Chase County, CHPal-1.

Fig. A. Untreated sample shows a strong reflec-
tion at 14.2A.

Fig. B. The glycolated sample relates an in-
crease in spacing of the 14.2A (002) peak to 17.3A,
implying a regular interstratification of 17A mont-
morillonite and 17A swelling chlorite.

Fig. C. After heating to 450 degrees Centi-
grade, a peak at 12A forms of 10A montmorillonite
and 14A chlorite second order reflections.

PLATE VIII

14.2A
Mont-swelling
chlorite(002)

10.04A
Illite(001)

7.2A
Mont-swelling
chlorite(004)

A

Untreated

17.2A
Mont-swelling
chlorite (002)

10.04A
Illite(001)

8.5A
Mont-swelling
chlorite(004)

B

Glycolated

10.04A
Illite (001)

12A
Mont-swelling
chlorite (002)

C

450 degrees C
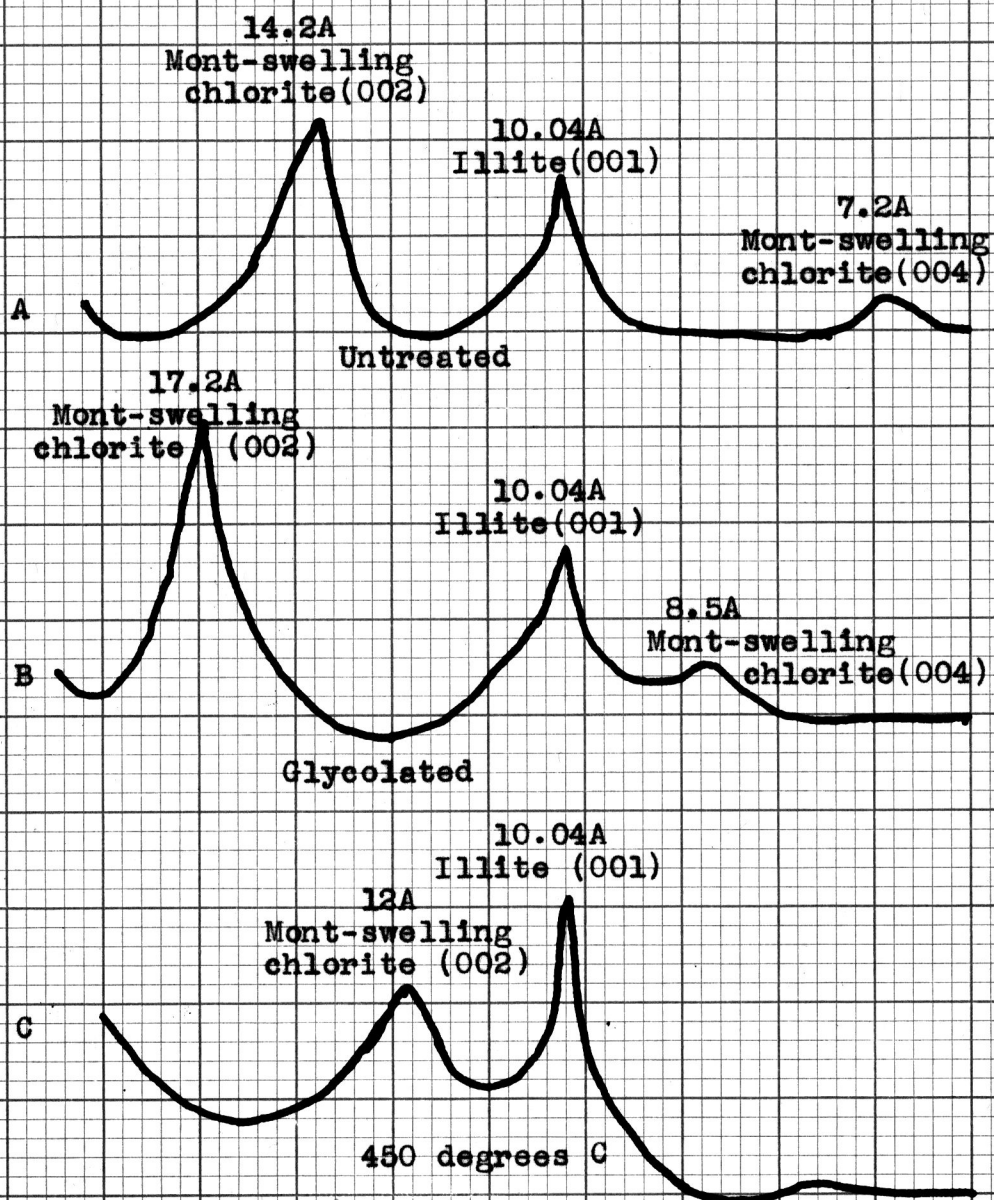
EXPLANATION OF PLATE IX

X-ray diffractometer smooth tracings of pattern
of Sample CYWe2-4.

Fig. A. Untreated pattern showing a regular se-
quence of reflections based on the superlattice spac-
ing of 29A.

Fig. B. Glycolation causes each reflection to
shift except that of illite. Notice the intensity of
the first two reflections is strong and subsequent
reflections absent.

Fig. C. If the interlayer is composed of mont-
morillonite and true vermiculite, no reflection shows
at 450 degrees Centigrade. Sample CHWel-1.

Fig. D. A sample of montmorillonite-swelling
vermiculite-chlorite shows a collapse of the super-
lattice to 24A. The reflection is due to addition
of 10A montmorillonite and 14A chlorite.

PLATE IX
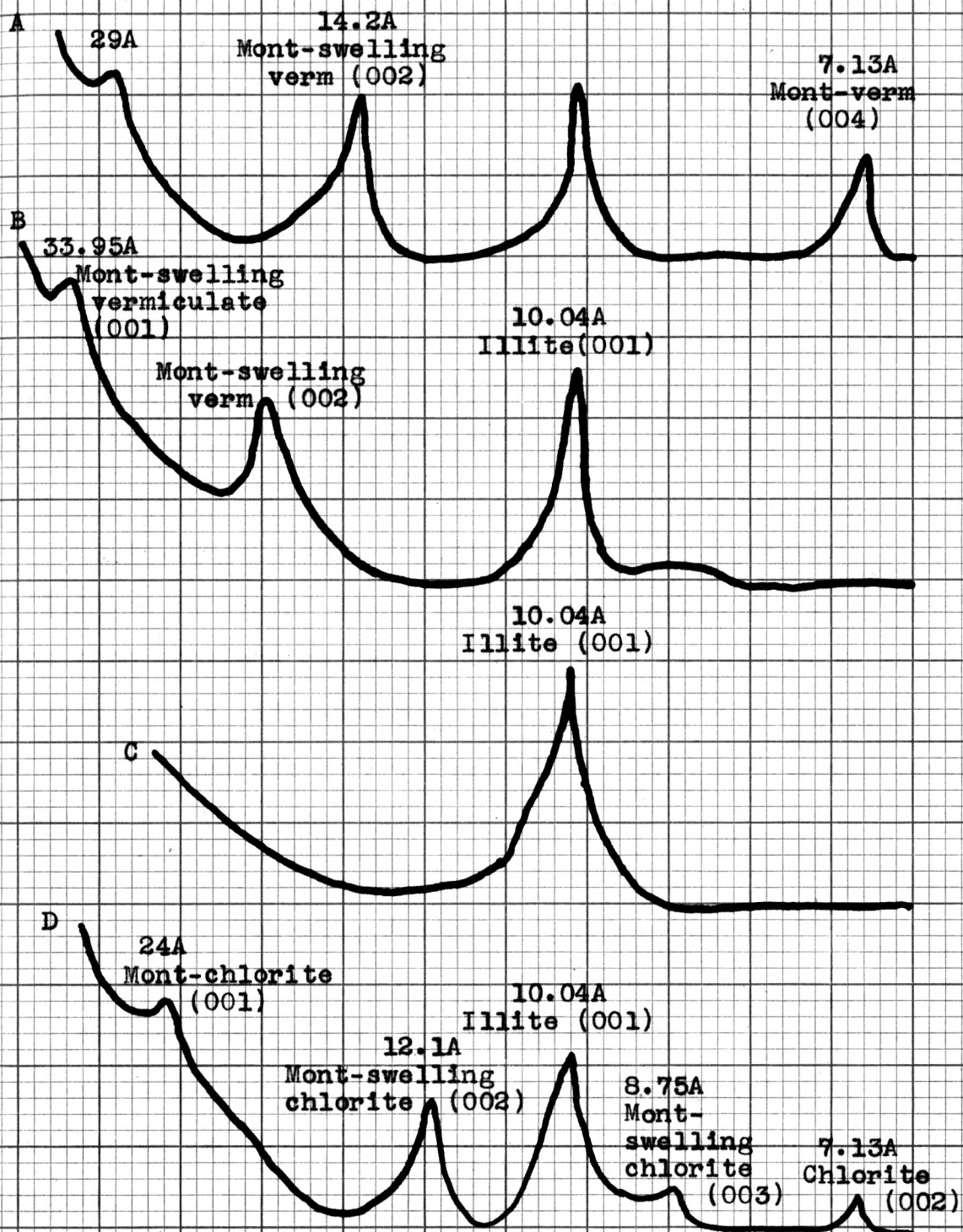
at higher temperatures designated the class of chlorite in the interlayer. The varieties of chlorite found in this investigation as interlayered components correlated with Classes 2, 4, 5, 6, and 7.

Class 3. When the first order reflection at 29A expanded to 34-35A after glycolation and collapsed to 24A after heating to 450 degrees, the interlayer was identified as a 1:1 interstratification of montmorillonite and "swelling chlorite". In this variety, all higher basal orders are absent above the 7.1A (004) reflection. The (002) reflection at 16.98A is the strongest.

Chlorite-vermiculite. When heated to 450 degrees, the 14.4A reflection collapses to 13.0-13.5A. No expansion after treatment with ethylene glycol occurs so this variety is an admixture of vermiculite and chlorite. The interlayer is usually random as only the average reflections of the first and second orders appear.

Non-clay Mineral Determination

Several non-clay minerals commonly can be identified in the clay-sized fraction. Four minerals were identified in this investigation as occurring in appreciable amounts in the colloidal suspension. Identification by means of X-ray diffraction was easy as each of these minerals has its strongest reflection in the 32- to 20-degree two theta range.

The strongest peak for calcite occurs at 3.035A. Another

calcite reflection at 3.86A often appears when calcite is a major constituent of the sample. The strongest reflection for dolomite is 2.89A. The variety of iron-rich dolomite, ankerite, has a strong reflection at 2.88A. The presence of goethite can be noted from rather broad reflection at an interval of 4.18-4.22A. Quartz was identified by its second strongest reflection at 4.26A. This peak will occur as a sharp shoulder on the low angle side of the goethite peak when the latter is present. The 4.26A reflection is about one-third as intense as the strongest quartz reflection at 3.33A. However, the latter holds the same d-spacing as the (003) reflection of illite, and consequently merely enhances the size and intensity of the illite reflection.

METHODS OF QUANTITATIVE EVALUATION

The relative percentages of the clay minerals in individual samples were calculated from measurements of the areas bounded by the curve and the background base line of the various basal reflections. In this investigation, the author used the first order reflections of illite, montmorillonite, and vermiculite, and the second order reflection for chlorite. All percentages were determined from diffractograms of glycolated samples.

The area under the (001) curve for illite approximates the actual percentage of the mineral in the sample so the reflecting power produced by the first order basal plane of illite would be near unity. Grim (1953) estimated that the (002) reflection of chlorite would be half of the measured value, or A/2. The (001)

reflection of montmorillonite has been reported by Brindley
(1951) to reflect four times as strong as illite so the correc-
tion factor would be $A_m/4$. Vermiculite appeared to have reflect-
ing powers intermediate between chlorite and montmorillonite and
was arbitrarily assigned a value of $A_v/3$. Where the samples
were not complicated by the presence of interstratified clays,
the percentages of the individual clay mineral would merely be
the fractional area donated by the mineral divided by the sum
of all component areas, or $A_m/\sum A_m + A_c \ldots A_n$.

The mixed layer clays were assumed to have an intrinsic curve
area which was dependent upon the relative number of each compon-
ent of the interlayer and the average reflecting power of each
type of layer. Brown and MacEwan (1950) derived a function in
which the intensity of a unique reflection was approximately
proportional to the product of the crystal structure factor, the
Lorentz polarization factor, and a ratio relating the angular
peak position of the interlayer to the ideal position of the
monomineralic phases and to the relative proportions of each
layer present. For the author's work, the percentages of inter-
layered components were treated as a simple ratio of the inter-
layer peak position to the maximum range between the monominer-
alic phases of the components. Therefore the differential re-
flecting power of the interlayer when treated as a reflecting
unit would be

$$\frac{pA}{pA + pB} (RP_{A_{max}} - RP_{B_{max}}) = D$$

where pA represents the observed proportions of the component in the interlayer, RP_A is the reflecting power of the mineral with the larger reflecting power, and D represents the fractional increase in reflecting power resulting from the layer percentages of A and B. Therefore the reflecting power of the interlayer would be equal to $D + RP_B$, the component with the lower reflecting power. For instance, if an interlayer had 50 per cent montmorillonite and 50 per cent chlorite, the maximum difference in reflecting power between the monomineralic phases would be two. Fifty per cent of two is one. Since each interlayered component donates half of the reflecting layers, if the latter value is added to the reflecting power of chlorite, the relative reflecting power of the interlayer would be approximately three. The actual sub-curve area for the first order reflection would be $A_{MC}/3$.

It must be stressed, however, that small variations in composition must be corrected for by use of polarization and structure factors before any finite measure of accuracy can be obtained. The sole object of the method was to obtain a relative percentage of interlayered clay as compared to the other clay constituents in the sample. This method suggests trends which can be traced from one sample to another and does not give the exact percentage of the interlayer in the sample. Variation diagrams of these relative percentage values were constructed and will be presented in a later section.

Areal ratios between first and second order chlorite reflections were used to give a measure of iron richness and also to

determine the approximate amounts of vermiculite. In the case
of vermiculite, the ratio (001)/(002) approaches or becomes
greater than unity. When the (001) reflection of chlorite was
masked by other reflections, the (003) reflection at 4.7A was
used. When the superlattice reflection held no coordination with
the other interlayers, the reflecting powers of the components
were increased by one unit due to the higher angle of reflection.

Carbonate minerals and quartz were compared on a 1:1 reflect-
ing power basis to first gather information as to rock type and
also to show local variations in carbonate mineralogy.

EXPLANATION OF TABLES 2 AND 3

A summary of the results of the relative clay mineral per-
centage determinations is tabulated in Table 2. These percent-
age values are further subdivided into two categories. One sub-
division represents the percentage sum of all free clay mineral
constituents plus the sum of the percentage fraction made up by
the interlayers. These values total 100 per cent and are repre-
sented in whole by unbracketed values. The second category in-
cludes a sum of all free clay mineral constituents plus the sum
of each mineral percentage of the interlayer. All of these
interlayer components were placed in parenthesis as an additive
sum of the free mineral percentages and in the column correspond-
ing to that mineral. Thus if a sample contained 90 per cent
illite and 10 per cent illite-montmorillonite interlayer having
a 1:1 stratification ratio, Table 2 shows 90+(5) under illite,

(5) under montmorillonite, and 10 under the I/M column. The dual summation would be 90 + 10 = 100 and 90 + (5) + (5) = 100. All minerals showing up in quantities too small to give an accurate percentage value were simply recorded as T, or trace. Any mineral which occurred as a part of more than one interlayer was bracketed in an order corresponding to that which it occurs in the table from left to right. Interlayer columns were designed to give the interlayer ratio and estimated stacking arrangement in addition to the percentage values.

Chlorite and illite classes are given as arabic numerals at the right of the percentage columns. When more than one class existed in a sample, the class notation follows the same sequence as the order for the mineral percentages. The two columns at the extreme right of the page represent sub-curve areal ratios of the illite (002)/(001) reflections and the chlorite (001)/ (002) reflections. Whenever a peak areal ratio corresponded to one class and the peak configuration fit into another, both class numbers are given; i.e., 13 or 81, the first number corresponding to the dominating characteristic. Chlorite possessing degrees of crystallinity greater than or equal to Class 4 often was found to have basal reflection intensities similar to Classes 1, 2, and 3, and was again assigned as a two-digit number.

Table 3 shows the relationships between calcite, dolomite, and quartz as percentage values calculated from X-ray random patterns. Calculations included both powder and colloidal values. True percentage relationships between the carbonates and insoluble residue are shown in Fig. 3 of the Appendix by means of

rectangular pie diagrams.

CLAY MINERAL IDENTIFICATION

Hollenberg Dolomite Member

The Hollenberg dolomite member of the Wellington formation was sampled from eight outcropping locations in seven counties (Fig. 1 in Appendix). Reference to Table 2 shows that the clay mineral assemblages do not vary remarkably from county to county although percentage-wise they vary a great deal.

Illite was the dominant clay mineral found and identified in all samples except in Chase and Clay counties where illite constituted around 60 and 40 per cent, respectively. Sample CYHbl-5 was identified as an arenaceous dolomite which seems to represent a gradational change between true carbonate environment of deposition and the limey silty shale deposition of the upper part of the Wellington formation. The Chase County sample, CHHbl-1, is a calcitic dolomite which has been badly weathered from long-time subaerial exposure.

Illite diffraction maxima of the Hollenberg X-ray patterns exhibit more or less sharp peak terminations and approach the general description for Class 1 illite. In addition, the calcitic dolomites which possess case hardening characteristics have second to first order peak ratios of so low a value that they fit properties of Class 3 iron-rich illite. The difference in clay mineralogy of the case hardened calcitic dolomites can

be seen comparing percentage values of samples WSHbl-1, DKHb2-2, MRHbl-3, and CHHbl-1 with percentage values of the remaining Hollenberg samples in Table 2.

Poorly crystalline montmorillonite was found in nearly all the samples except the upper two units of the section in central Dickinson County. The montmorillonite percentage increases toward the top of the section in places where this comparison can be made. In the Hollenberg, mixed-layer clays are primarily random interstratifications with only sample CYHbl-5 from Clay County showing regular interstratification. In the latter, chlorite is regularly interlayered with montmorillonite on the basis of a 1:1 ratio. Some vermiculite-chlorite is interstratified in what seems to be a 1:1 ratio, but the absence of higher order diffraction maxima suggests that the stacking arrangement is random, and therefore the reflection is an average value of the first order d-spacings for the two minerals involved.

The most striking trend is shown by comparing the chlorites. All Morris, Chase, Riley, and Washington county chlorites are iron-rich poorly crystalline, whereas the chlorites from Clay and Dickinson counties are iron-rich but are evidently much better crystalline. This phenomenon of good crystallinity grades to poorer crystallinity of the chlorite in all directions away from these two counties. One reason for this trend could be that the Hollenberg in Clay and Dickinson counties have not been exposed to weathering processes for as long a time as the rest of the sections.

Table 2. Summary of the clay minerals and interlayers in the limestones and shales of the Lower Sumner Group and Upper Chase Group.

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	I/C	C/M	V/C	Icn	Ccn	I(002)/(001)	C(001)/(002)
WELLINGTON FORMATION													
Hollenberg Member													
WSHb1-1	C-Dol	82+(7)	8+(1)	-	2	*8(7:1)	-	-	-	13	2	.095	.000
RLHb1-1	C-Dol	91	2	-	7	T	-	-	-	1	2	.300	.000
CYHb2-1	Dol	91	-	-	9	T	T	-	-	1	2	.250	.000
CYHb1-5	Sa-Dol	42	(28)	-	2+(28)	-	-	**56(1:1)	-	1	2(6)	.450	.333
CYHb1-4	C-Dol	88	(2)	-	9+(1)	-	-	*3(1:2)	-	13	3(3)	.160	.844
DKHb1-1	Dol	90	2	3+(1)	3+(1)	-	-	-	*2(1:1)	1	4(4)	.260	4.000
DKHb2-1A	Dol	99	-	T	1	*T(9:1)	-	-	-	1	23	.294	.800
DKHb2-1B	Sh-Dol	95	1	(1)	2+)1)	T	-	-	*2(1:1)	1	2(2)	.269	1.540
MRHb1-3	C-Dol	77	11	4	8	T	-	-	-	13	3	.110	1.670
MRHb1-2	Dol	78	7	-	15	*T(4:1)	*T(3:1)	T	-	13	23	.260	.690
MRHb1-1	Dol	90	1	-	9	-	-	-	-	1	2	.500	.500
CHHb1-1	C-Dol	57	43	-	-	-	-	-	-	13	-	.100	-
DKHb2-2	Dol	93	-	-	7	-	-	-	-	13	6	.120	1.080
WELLINGTON SHALE													
WSWe1-2	Sh	77	18	-	4	*1(3:2)	-	-	-	1	2	.330	.000
WSWe1-1	Dol-Sh	97	T	-	3	T	-	-	-	23	2	.121	.333
WSWe2-1	Dol-Sh	94	1	-	5	T	-	-	-	1	5	.365	.500
RLWe1-8	Dol-Sh	95	2	T	3	T	-	T	T	1	6	.268	.320
RLWe1-7	Dol-Sh	91	4	T	5	T	*T(1:1)	-	-	1	6	.250	.300

Symbols: C-Dol(calcitic dolomite), Ls(limestone), MLs(magnesian limestone), Dol(dolomite), Dol-Ls(dolomitic limestone), Sh-Dol(shaly dolomite), Sh-Ls(shaly limestone), Ls-Sh(calcareous shale), Dol-Sh(dolomitic shale), Sh(shale), Si-Dol(Ls)(siliceous dolomite or limestone), Ch-Dol(ls)(cherty dolomite or limestone), Sa-Dol(arenaceous dolomite).

SwC(swelling chlorite), Icn(class of illite), Ccn(class of chlorite), I(002)/(001) ratio of peak areas of first and second order illite reflections), (n)(percentage of mineral in interlayer), *random, **(regular interlayer), #(superlattice reflection), a:b(ratio of interlayer components).

Table 2 (Cont.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	V/C	M/SwC	Icn	Ccn	$I\frac{(002)}{(001)}$	$C\frac{(001)}{(002)}$
RLWel-6	Sh	84	18	-	5	T	-	T	-	-	1	2	.366	.383
RLWel-5	Dol-Sh	95	T	-	5	-	-	-	-	-	13	62	.140	.029
RLWel-4	Sh	94	1	T	5	-	-	T	-	-	1	2	.300	.333
RLWel-3	Dol-Sh	84	9	T	7	T	-	-	-	-	1	52	.295	.350
RLWel-2	Dol-Sh	90	(7)	-	2+(1)	-	-	*8(1:9)	-	-	13	5(5)	.131	.200
RLWel-1	Dol-Sh	93	4	-	3	T	-	-	-	-	1	52	.241	.500
CYWel-7	Sh-Dol	20	(35+2.5)	(2.5)	2+(35)	-	-	**70(1:1)	-	#**5(1:1)		2 23(6)(81)	.600	.800
CYWel-6	Ls	24	(34+3)	-	2+(34+3)	-	-	**68(1:1)	-	#**6(1:1)		2 4(6)(84)	.380	.500
CYWel-3	Sh	34	(26+7)	(7)	(26)	-	-	**52(1:1)	-	#**14(1:1)		1 1(6)(81)	.238	-
CYWel-2	Sh	47	(26)	-	1+(26)	-	-	#**52(1:1)	-	-	1	4(6)	.260	.250
CYWel-1	Sh	40	(35)	-	1+(24)	-	-	#**59(1:1)	T	-	2	6(6)	.300	.000
CYWe2-5	Sh	51	(23+1)	(1)	1+(23)	-	-	**46(1:1)	-	#**2(1:1)		2 2(62)(81)	.320	-
CYWe2-4	Sh	45	(33,25)x	(5)	(22,25)	-	-	#**55(2:3)	-	-	2	(72)	.364	.000
CYWe2-3	Sh	43	(28)	(T)	(28+T)	T	-	#**56(1:1)	*1(7:3)-		1	(72)	.248	.000
CYWe2-2	Sh-Ls	59	(22)	-	3+(16)	T	-	*38(4:9)	-	#**T	1	2(4)	.339	.500
CYWe2-1	Sh	46	(26+3)	(3)	2+(20)	T	-	*46(4:9)	-#**6(1:1)		1	2(62)	.358	.000
												63(5)	.400	1.290
DKWel-3	Dol-Sh	90	(3)	1	3+(3)	T	-	**6(1:1)	T	-	1	63(5)	.481	1.000
DKWel-2	Dol-Sh	88	(4.5)	T	3+(4.5)	-	-	**9(1:1)	-	-	1	43(5)	.490	.900
DKWel-1	Dol-Sh	77	(10)	-	4+(9)	-	-	**19(1:1)	-	-	1	2	.300	3.420
DKWe2-2	Sh-Dol	90	T	7	3	T	-	-	-	-	1	2	.440	.200
DKWe2-1	Sh	94	(2)	(3)	1	-	#**5(5:3)	-	-	-	1			

x This sample could possibly have up to 5 per cent random vermiculite, making the interlayer ratio 45C/45M/5V.

Table 2 (Cont.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	V/C	M/SwC	Icn	Ccn	I $\frac{(002)}{(001)}$	C $\frac{(001)}{(002)}$
							Clay minerals							
MRWel-6	Sh	85+(3)	(4)+(1)	(4)	3	*4(7:3)	**8(1:1)	-	-	-	2	2	.223	.500
MRWel-5	Dol-Ls	90	(5)	(3)	2	T	*8(1:2)	-	-	-	13	3	.120	1.000
MRWel-4	Sh	96	-	-	4	T	-	-	-	-	12	2	.324	.000
MRWel-3	Sh	97	-	-	3	T	-	-	-	-	2	23	.268	.571
MRWel-2	Sh	98	1	-	1	-	-	-	-	-	13	2	.162	.000
MRWel-1	Sh	97	-	-	3	-	-	-	-	-	2	2	.200	.236
CHWel-1	Ls-Sh	30	(59+2)	(7+2)	-	-	*66(1:9)	-	-	**4(1:1)	2	(81)	.240	-

WOLFCAMP SERIES - NOLANS FORMATION
  Herington member

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	V/C	M/SwC	Icn	Ccn	I $\frac{(002)}{(001)}$	C $\frac{(001)}{(002)}$
WSHel-7	Dol	87	1	1	11	T	-	-	-	-	1	4	.258	.459
WSHel-6	Dol	95	1	-	4	T	-	-	-	-	13	2	.094	.286
WSHel-5	Si-Dol	87	(T)	(1)	10+(T)	*1(6:7)	-	-	**2(1:1)	-	13	5(2)	.158	.607
WSHel-4	Dol	88+(3)	(1)	2	6	*4(4:1)	-	-	T	-	1	4	.204	.813
WSHel-3	Sh	92	1	T	7	T	-	-	-	-	1	4	.423	.676
WSHel-2	Si-Dol	98	T	-	2	T	-	-	-	-	1	2	.342	.000
WSHel-1	Dol	88+(3)	(1)	-	8	*4(3:1)	-	-	-	-	13	4	.144	.466
RLHe2-5	Dol	96	T	-	4+T	T	-	-	-	-	2	2+4	.276	.286
RLHe2-4	Sh-Dol-Ls	89	3	(T)	7+(T)	T	-	-	*1(1:1)	-	1	2	.214	1.000
RLHe2-3	C-Dol	91	T	9+(T)	(T)	T	-	-	T	-	13	-	.107	-
RLHe2-2	Sh-MLs	88	3+(1)	2+(3)	3	-	*4(7:3)	-	-	-	1	2	.200	1.060
RLHe2-1	Dol	88	4+	T	8+(T)	T	-	-	T	-	1	2	.231	.500
RLHel-4	Dol	89	-	1	10	T	-	-	-	-	13	3	.167	1.000
RLHel-3	Dol	90	(5)	2+(2)	1	T	*7(3:7)	-	-	-	1	2	.325	5.000
RLHel-2	Dol	91	-	-	9	T	-	-	-	-	1	23	.338	.770
RLHel-1	Sh-Dol	90	(1)	1+(2)	6	-	*3(7:3)	-	-	-	13	2	.127	.666
DKHe2-5	Dol	(73)	(1+3+9)	1+(9)	5	*15(9:1) *61(25:1)	**18(1:1)	-	-	-	13	2	.193	1.090

Table 2 (Cont.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	I/C	V/C	M/SwC	Icn	Ccn	I(002)/(001)	C(001)/(002)
								Clay minerals							
DKHe2-4	Dol	76	(8)	(3)	3+(10)	T	-	*18(7:6)	-	-	-	1	2(4)	.208	1.125
DKHe2-3	Dol	77	(12)	T	3+(8)	T	-	*20(2:3)	-	-	-	13	2(4)	.163	.800
DKHe2-2	Dol	81	(8)	(5)	6	T	*13(2:3)	-	-	-	-	3	2	.106	.333
DKHe2-1	Si-Dol	78	T	9	13	T	-	-	-	-	-	3	2	.077	1.000
DKHe1-3	Dol	70	(11)	2+(11)	6	-	**22(1:1)	-	-	-	-	1	2	.204	1.000
DKHe1-2	Si-Dol	73	(8)	7+(2)	10	-	*10(1:4)	-	-	-	-	1	2	.368	.777
DKHe1-1	Si-Dol	67	(16)	2+(9)	4	T	*27(2:3)	-	-	-	-	1	2	.284	.836
MRHe1-2	Dol	73	15	3	9	T	-	-	-	-	-	1	52	.700	1.080
MRHe1-1	Dol	84+(2)	6+	2	6	*2(5:1)	-	-	-	-	-	1	53	.376	.930
MRHe2-2	Dol	88	6	1	5	T	* -	-	-	-	-	1	52	.264	.724
MRHe2-1	Dol-Ls	77	(8)	2+(8)	5	T	**16(1:1)	-	-	-	-	23	2	.060	3.000
CHHe1-6	Dol	44	(33+1)	(20+1)	1+(T)	T	*53(2:3)	-	-	-	#**2(1:1)	2	2(4)	.600	.000
CHHe1-5	Dol	35	(36+5)	(19+5)	1+(T)	-	*55(1:2)	-	-	-	#***10 (1:1)	23	2(4)	.192	.000
CHHe1-4	Ch-Dol-Ls	42	(34+1)	(21+1)	1	-	*55(2:3)	-	-	-	#**2(1:1)	2	2(81)	.210	.000
CHHe1-3	Sh-Dol	49	(31+3)	(3)	1+(13)	-	-	*44(3:7)	-	-	#***6(1:1)	1	2(4)(81)	.405	.000
CHHe1-2	MLs	53	47	-	-	-	-	-	-	-	-	23	-	.100	-
CHHe1-1	Dol	42	(35+1)	(18+1)	3	-	*53(2:3)	-	-	-	#**2(1:1)	1	2(81)	.435	.250
MNHe1-14	Dol	86	T	4	10	T	-	-	*T(3:1)	-	-	1	2	.368	.667
MNHe1-13	Dol	92	T	-	8	T	-	-	*T(3:1)	-	-	1	3	.425	.800
MNHe1-12	Dol	91	T	-	9	T	-	-	-	-	-	1	23	.250	.700
MNHe1-11	Dol	89	T	2	9	T	-	-	-	-	-	2	2	.430	.333
MNHe1-10	Sh	27	53	13+(1)	7+(T)	T	-	-	-	T	-	23	2(2)	.146	4.720
MNHe1-9	Dol	88	1	5	6	T	-	-	-	T	-	2	2	.222	2.430
MNHe1-8	Dol	92	1	T	6+(T)	T	-	-	*1(1:1)	-	-	12	2(5)	.209	.273

Table 2 (Cont.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	V/C	M/SwC	Icn	Ccn	I$\frac{(002)}{(001)}$	C$\frac{(001)}{(002)}$
								Clay minerals						
MNHel-7	Sh	96	T	-	4	T	-	-	-	-	1	42	.515	.039
MNHel-6	Dol	91	1	T	7	-	-	-	T	-	12	42+6	.208	.118
MNHel-5	Sh	91	(T)	(T)	7+1	-	*1(9:1)	-	-	-	3	4+6	.086	.333
MNHel-4	Sh	92	(3)	(1)	4	T	*4(1:2)	-	*-	-	1	4	.278	.000
MNHel-3	Dol	91	T	3+	6+(T)	T	-	-	*1(1:6)	-	23	2(5)	.117	1.000
MNHel-2	Sh	92	(1)	(T)	4+(3)	-	-	*3(7:3)	T	-	2	2(5)	.332	.525
MNHel-1	Dol	91	(1)	(5)	3+(1)	T	*3(3:2) *3(5:4)	-	-	-	13	2	.185	2.000
Paddock Shale Member														
WSPal-1	Dol-Sh	92	(T)	-	7+(T)	T	-	*1(1:5)	-	-	1	6(6)	.320	.200
RLPa3-2	Dol-Sh	83	(7)	2	1+(7)	-	-	**14(1:1)	-	-	1	2(4)	.211	2.333
RLPa3-1	Dol-Sh	84	(6)	-	3+(7)	-	-	*13(7:6)	-	-	1	4(5)	.370	.000
RLPa2-1	Sh	85	(2+3)	T	5+(4+1)	T	-	*6(3:5) *4(3:7)	-	-	13	2(4+2)	.163	.250
RLPal-2	Sh	90	(2)	1	5+(2)	-	-	*4(5:7)	-	-	1	4(2)	.319	.428
RLPal-1	Sh	91	(3)	T	2+(4)	-	-	*7(3:2)	-	-	1	2(4)	.351	.500
DKPal-1	Dol-Sh	73	(11)	-	5+(11)	T	-	**22(1:1)	-	-	1	43(5)	.332	.800
MRPa2-3	Dol-Sh	82	(8)	T	6+(4)	T	-	*12(1:2)	-	-	1	4(4)	.350	.824
MRPa2-2	Sh	86	(6.5)	-	1+(6.5)	T	-	#**13(1:1)	-	-	2	23(42)	.274	.850
MRPa2-1	Sh	86	(6)	T	2+(6)	T	-	#**12(1:1)	-	-	2	23(42)	.338	.960
MRPal-2	Sh-Dol	82	5+(3)	T	7+(3)	*T(7:3)	-	**6(1:1)	-	-	1	3(4)	.264	1.000
MRPal-1	Sh	82	(13)	-	3+(2)	T	-	*15(1:9)	-	-	1	2(4)	.200	.666
CHPal-1	Dol-Sh	51	(32+T)	(T)	3+(13)	-	-	*45(3:7)	-	#**1 (1:1)	1	3(42) (81)	.200	.800
MNPal-1	Sh	94	(1+1)	(1)	2+(1)	T	**2(1:1)	**2(1:1)	-	-	13	4(2)	.083	2.000

Table 2 (Cont.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	M/SwC	Icn	Ccn	I$\frac{(002)}{(001)}$	C$\frac{(001)}{(002)}$
Krider Limestone Member													
RLKrl-1	Dol	60	(15)	-	4+(15)	T	-	**30(1:1)	-	1	6(6)	.322	.400
MRKrl-3	MLs	85+(1.4)	(+4.3) 2+(4.3)	2		*1(7:3)	*10(6:6:2)	-	-	12	2	.405	1.600
MRKrl-2	C-Dol-Sh	(4.6+1) 83+(8+)	2+(4.6)	2+(1)		*1(49:1) *10(8:8:1)		-	#**2(1:1)	1	2(82)	.427	1.870
MRKrl-1	Ls	90	(3.5)	(2.5)	4	T	*6(2:3)	-	-	2	2	.210	.500
ODELL SHALE								**6(1:1)					
RLOdl-1	Dol-Sh	79 (3+3+2+2.5)		- 2+(3+2+1+2.5)		T	-	*5(2:3) *3(3:7)	#**5 (1:1)	1	5(5) (82)	.500	.836
MROdl-2	Ls-Sh	98	(T)	-	1+(T)	T	*1(2:3)	-	-	1	2	.278	.000
MORdl-2	Sh	80	(13)	-	4+(3)	-	-	*16(1:5)	-	1	3(4)	.510	.800
DKOdl-2	Sh	98	-	-	2	-	-	-	-	1	2	.406	.307
DKOdl-1	Dol-Sh	96	1	-	3	T	-	-	-	1	2	.242	.357
WINFIELD LIMESTONE FORMATION													
Cresswell Limestone Member													
RLCrl-2	Si-Ls	72	(17)	4+(4)	4	T	*20(1:5)	-	-	12	2	.256	1.333
RLCrl-1	Si-Ls	76	(17)	(4)	3	-	*21(1:5)	-	-	1	3	.237	.833
DKCrl-2	Si-Dol	72	(8)	-	15+(5)	-	-	*13(2:3)	-	13	23(5)	.160	.700
DKCrl-1	Ch-Dol	77	(6)	-	14+(3)	T	-	*9(3:7)	-	1	3(5)	.482	.835
DKCr2-5	Dol-Ls	75	(T+7.5)	5+(7.5)	4	*1(7:3)	**15(1:1)	-	-	23	2	.133	1.690
DKCr2-4	Dol-Ls	74	(12)	T	5(9)	T **T	*21(2:3)	-	-	1	4(4)	.259	1.808
DKCr2-3x	Si-Ls	68	(12+1)	3+(T)	2+(12)	T	-	**24(1:1)	#**3 (1:1)	1	4(4) (81)	.242	2.000

Table 2 (Cont.).

Geologic section	Lithology	Illite	Mont	Verm	Chlorite	I/M	V/M	C/M	V/C	M/Sw	C	Icn	Ccn	I(002)/(001)	C(001)/(002)
DKCr2-2	Si-Ls	70	(11)	5+(11)	3	T	**22(1:1)	-	-	-		1	2	.360	2.240
DKCr2-1	Ch-Ls	80	(6)	5+(6)	3	-	**12(1:1)	-	-	-		13	2	.154	1.850
Grant Shale Member															
RLGr1-3	Sh-Ls	74	(10.5)	1	4+(10.5)	-	-	**21(1:1)	-	-		1	4(4)	.395	1.000
RLGr1-2	Ls-Sh	78	(12)	-	3+(7)	T	-	*19(2:3)	-	-		12	4(4)	.243	.600
RLGr1-1	Ls-Sh	78	(8+1)	(1+1)	2+(8+1)	T	-	**2(1:1)				1	4(6)	.300	1.290
								**16(1:1)	#***2(1:1)				(81)		
DKGr1-3	Sh-Dol	74	(9+1.5)	(1.5)	5+(9)	T	-	#**18(1:1)	-			1	4(6)	.409	1.000
									#**3(1:1)				(81)		
DKGr1-2	Dol-Sh	79	(6)	1	6+(7)	T	-	#**14(3:2)	-	-		1	42(62)	.294	.770
DKGr1-1	Dol-Sh	79	(6)	1	3+(8)	T	-	#**14(3:2)	-	-		1	4(6)	.425	.644
DKGr2-1	Sh-Dol-Ls	61	(19+3)	(13+3)	1	T	*32(2:3)	-	#**6(1:1)			2	2(81)	.454	.600
BUGr1-1	Sh	89	4+(1)	-	4+(2)	T	-	*3(2:1)	-	-		1	23(5)	.485	.600
Stovall Limestone Member															
RLSt1-2	Ch-Ls	85	(2)	(9)	4+	T	*11(5:1)	-	T	-		1	2	.473	.830
RLSt1-1	Ls	76	(11)	T	2+(11)	T	-	**22(1:1)	-	-		23	2(4)	.219	.900
DKSt1-1	Ch-Dol	87+(2)	(3)	1	4+(3)	*2(4:1)	-	**6(1:1)	-	-		1	23(5)	.317	1.200
CHSt1-3	Ch-ML	56	(33)	(7)	4	T	*40(5:1)	-	-	-		1	2	.363	.250
CHSt1-2	Chert	91	-	-	9	-	-	-	-	-		1	2	.333	.000
CHSt1-1	Ch-Ls	64	(6)	+(25)	4	-	*31(5:1)	-	-	-		13	2	.154	.890
DOYLE SHALE FORMATION															
Gage Shale Member															
RLGg1-2	Sh	75	(8)	(1)	5+(5+6)	T	-	*14(4:5)	*6(1:7)	-		2	2(6,6)	.248	1.272

Table 2 (Cont.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	C/M	I/C	V/C	M/SwC	Icn	Ccn	I(002)/(001)	C(001)/(002)
RLGg1-1	Sh	81	4+(5)	1	4+(5)	T	-	**10(1:1)	-	-	-	2	4(4)	.440	1.000
RLGg2-1	Sh	81	(9)	-	2+(9)	T	-	**18(1:1)	-	-	-	1	2(6)	.500	1.000
DKGg1-1	Sh-Dol	79	(8+1)	(1)	3+(8)	-	-	**16(1:1)	-	-	#**2(1:1)	1	4(7)(81)	.480	1.290
CHGg1-6	Ls-Sh	44	(28)	-	(28)	T	-	-	-	-	#**56(1:1)	1	(81)	.241	.000
CHGg1-5	Ls-Sh	88	(8)	(3)	1	T	*11(2:7)	-	-	-	-	1	2	.333	.000
CHGg1-4	Dol	83	15	T	2	T	T	-	-	-	-	1	2	.323	1.121
CHGg1-3	Ls-Sh	73+(5)	3+(2+14)	2+(2)	2	*7(7:2) *16(1:7)	-	-	-	-	-	1	2	.202	1.667
CHGg1-2	Ls-Sh	86	10+	1+	3+	-	-	T	-	T	-	1	2	.250	1.000
CHGg1-1	Ls-Sh	85	10+	T	4+	T	-	*1(1:7)	-	-	-	1	2(5)	.252	.584
BUGg1-2	Sh	97	1	-	2	T	-	-	-	-	-	23	2	.153	.000
BUGg1-1	Sh	52	(15)	-	3+(30)	-	-	#**45(2:1)	-	-	-	12	5(7)	.353	.800
Towanda Limestone Member															
RLTo1-3	Ls	90	4	3	3	-	-	-	-	-	-	13	3	.140	1.480
RLTo1-2	Ls	87	9	3	-	*1(7:3)	-	-	-	-	-	13	-	.020	-
RLTo1-1	Ls	89	4	4	3	T	-	-	-	T	-	1	23	.214	2.200
CHTo1-5	MLs	97+	-	1+(1)	1	T	-	-	*1(1:5)	-	-	1	2	.405	1.620
CHTo1-4	Ls-Sh	90+	6+	T+(4)	-	T	-	-	*4(1:8)	-	-	1	(1)	.600	-
CHTo1-3	Ls	82	18	-	-	T	-	-	-	-	-	23	-	.182	-
CHTo1-2	Ls	66	34	-	-	-	-	-	-	-	-	2	-	.266	-
CHTo1-1	Ls	89	6	T	5	-	-	-	-	-	-	12	23	.400	.500
BUTo1-2	Si-Dol	83	6	-	10	T	-	-	-	-	-	23	2	.158	.000
BUTo1-1	Dol	94	-	1+(1)	4:(1)	T	-	-	-	**2(1:1)	-	2	2(4)	.333	1.500
BUTo2-1	Si-Dol	87	10	-	3	T	-	-	-	-	-	2	2	.300	.000

Table 2 (Concl.).

Geologic section	Lith-ology	Il-lite	Mont	Verm	Chlo-rite	I/M	V/M	I/C	V/C	Icn	Ccn	I$\frac{(002)}{(001)}$	C$\frac{(001)}{(002)}$
Holmesville Shale Member													
RLHv1-4	Sh-Ls	89	9	2	-	T	T	-	-	2	-	.301	-
RLHv1-3	Sh	97	1+(1)	(1)	T	*T(7:3)	*2(3:7)	-	-	12	-	.278	-
RLHv1-2	Sh	98	T	2	T	T	-	-	-	12	3	.330	6.670
RLHv1-1	Sh	98	-	T	2	T	-	-	-	23	3	.220	1.000
CHHv2-3	Sh	87+(2)	(3)	(3+4)	-	*1(7:1)	*7(4:3)	**5(1:1)	-	1	-	.414	.000
CHHv2-2	Sh	95	T	T	5	T	-	T	-	23	2	.152	.500
CHHv2-1	Sh	98	-	-	2	T	-	-	-	13	2	.085	.334
CHHv1-4	Sh	58	42	-	-	T	-	-	-	1	-	.222	-
CHHv1-3	Sh	93	(1)	2+(3)	1	-	*4(4:1)	-	-	12	2	.200	5.340
CHHv1-2	MLs	94	1	2	3	-	T	-	-	1	2	.274	1.090
CHHv1-1	Sh	98	-	T	2	-	-	-	T	1	23	.323	.625
BUHv1-2	Dol-Sh	75	19	-	6	-	-	-	-	23	2	.075	.000
BUHv1-1	Sh-Dol	87	9	-	2	*2(7:1)	-	-	-	1	2	.250	.000
BUHv2-1	Sh	84	12	2	1	*1(8:1)	-	-	-	1	2	.229	3.000
BARNESTON FORMATION													
Fort Riley Member													
CHFr2-2	Dol	94	-	1	5	-	-	-	-	13	4	.075	.429
CHFr2-1	Sh	99	-	-	1	T	-	-	-	2	2	.306	.000
CHFr1-10	Dol	86+(1)	6+(1)	6+(1)	T	*1(3:1)	-	*1(1:3)	-	23	2	.167	8.000
CHFr1-9	Si-Dol	90	-	(2)	6+(2)	T	-	-	**4(1:1)	13	5(5)	.182	.710
CHFr1-8	Dol-Ls	93	-	(1.5)	4+(1.5)	T	-	T	**3(1:1)	13	5(5)	.188	.845
CHFr1-7	Dol	86	T	(3.5)	7+(3.5)	T	-	T	**7(1:1)	1	5(5)	.735	.980
CHFr1-6	Sh-Dol	86	2	5	6	T	-	-	T	13	2	.133	.750
CHFr1-5	Dol-Sh	94	-	1	5	-	-	-	-	1	4	.226	.182
CHFr1-4	Dol	93	1+	(2)	4	-	*3(6:1)	-	-	13	42	.100	.530
CHFr1-3	Dol-Sh	93	-	3	4	T	-	-	-	13	2	.152	1.170
CHFr1-2	Dol-Ls-Sh	94	-	2	4	T	-	-	-	23	2	.080	.890
CHFr1-1	Dol	95+	(T)	(T)	3+	*1(2:1)	-	-	*1(2:1)	23	2(4)	.179	.622

The results of the carbonate percentage determinations and insoluble residue percentage determinations are given in Table 3. The insoluble residue percentages are very uniform with the exception of CYHb1-5 and DKHb2-1B which represent transitional beds from carbonate rock to shale. The rocks with case hardening properties have higher insoluble residue percentages with the exception of CHHb1-1 which has the lowest of all the samples examined. The latter is explained on the basis of extreme exposure to subaerial weathering. Incipient relationships between calcite, dolomite, and insoluble residue are given in cross section in Fig. 3 of the Appendix. This chart shows the regional trend of carbonate relationships from north to south across Kansas. In addition, all samples except those of Clay County show a distinct 4.21A peak which was identified as goethite. The quantity of goethite in a sample was measured by the color of the filtrate in the insoluble residue process. Most of the samples containing abundant colloidal goethite had an orange to red brown filtrate color.

Pearl Shale

Immediately underlying the Hollenberg member is the Pearl shale member of the Wellington formation. This shale possesses primarily the same clay mineralogy as was described for the Hollenberg. The most apparent difference is in the state of crystallinity. The illite diffraction maxima are broader than those of the illites identified in the Hollenberg. This broadening

characteristic has been attributed to the hydration of potassium by Dalton, Swineford, and Jewett (1956), and by degration of the illite by Weaver (1958). The author used Class 2 for those illites which have peaks of a definite blunted nature. Where the maxima were intermediate between acute and rounded, the table designation was Class 12. The Class 2 and 12 illites were dominant in Clay and Morris counties.

The Pearl shale of Washington, Riley, and Morris counties is very similar in respect to clay mineralogy in that all three sections have illite dominancy, a rather constant chlorite percentage, a decrease in montmorillonite from top of the section to the bottom, abundant colloidal dolomite, and very little evidence of interlayered clay minerals. Nearly all chlorites are in the iron-rich state and are poorly crystalline in the Washington and Morris county samples, and are well crystalline in the Riley County samples. Only samples RLWe1-2 and MRWe1-6 have noticeable chlorite interlayered with montmorillonite. Field observations showed that both zones were better protected from weathering forces.

The shale section from southern Clay County was actually sampled from two locations. One location designated as We1 was in contact with the Hollenberg, and the other, We2, was sampled near the top of the underlying Herington dolomite. The interlayered montmorillonite-chlorite, montmorillonite-vermiculite, and montmorillonite-swelling chlorite-vermiculite of Clay and Dickinson counties approach regularity of interstratification with either a 1:1 or 2:3 ratio prevailing, and often produce a well

defined superlattice reflection at about 29A on untreated samples. The regularly interstratified montmorillonite swelling chlorite displays only the first order superlattice reflection of the integrated basal series. Since heating to 450 degrees Centigrade destroys the reflection, the author contends that the so-called swelling chlorite is actually a swelling vermiculite. This designation would explain the absence of successive higher order reflections of the interlayer. Sample CYWe2-2 is a thin secondary limestone where the illite percentage has increased and the percentage of interlayered clay has decreased. This relationship, however, reverses itself in the underlying shale, CYWe2-1.

Free montmorillonite was completely absent and free chlorite appears in negligible quantities of one to two per cent in the Clay and northern Dickinson County samples. The chlorite involved in the interlayer was considered to be very well crystalline and usually withstands heating to 620 degrees and sometimes to 700 degrees, which approaches the thermal stability range for metamorphic chlorites.

In Chase County, the upper Pearl shale is a random interlayer complex where montmorillonite is interlayered with vermiculite having both expanding and non-expanding properties. The 17A expanded vermiculite layer was identified as forming a 1:1 ratio with montmorillonite layers in the glycol-solvated 33.95A superlattice structure. The 16.8A peak is possibly the second order multiple reflection of the superlattice reflection and has some randomly interlayered non-expanding vermiculite. Another possibility for the latter is that it is a randomly interstratified

montmorillonite-vermiculite complex in which the vermiculite does
not expand and would be in this case an independent phase not
based on the superlattice.

In summary the Wellington shale shows the following trends:
(1) An increase in interlayer montmorillonite-chlorite in the
west central part of the area and an accompanying decrease in
both free montmorillonite and free chlorite; (2) there is a trend
toward poorer crystallinity to the south, i.e., in Washington,
Riley, Clay, and northern Dickinson counties, the chlorite is
well crystalline grading to poorly crystalline chlorite in Morris,
southern Dickinson, and Chase counties; (3) illite shows poorer
crystallinity in the Pearl shale than in the Hollenberg dolomite;
(4) the appearance of the superlattice reflection of montmoril-
lonite-chlorite and montmorillonite-vermiculite interlayers is
dominant. The Hollenberg shows no such superlattice reflections
which are strong enough to be recorded by means of X-ray diffrac-
tion. (5) Samples CYWel-7, CYWel-6, and WSWel-2 are from the
Wellington shale immediately overlying the Hollenberg. These
samples show a trend toward further decrease in illite and an in-
crease in interlayer constituents.

Herington Dolomite

The Herington member is the top stratigraphic member of the
Nolans formation which is stratigraphically at the top of the
strata marking the Wolfcamp Series in Kansas. The clay mineral-
ogic trend in the Herington holds much similarity to that discussed

Table 3. A summary of the **calcite-dolomite-quartz** relationships and the insoluble residue percentages of the **carbonate rocks.**

Geologic section	Lithology	Powder sample			Colloidal fraction			Insoluble residue percentage	Filtrate color
		Cal-cite	Dolo-mite	Quartz	Cal-cite	Dolo-mite	Quartz		
HOLLENBERG MEMBER									
WSHb1-1	C-Dol	14	82	4	16	84	-	9.63	Dk-orange
RLHb1-1	C-Dol	19	76	5	16	79	5	5.31	Red
CYHb1-1	Dol	9	89	2	1	97	2	3.88	Dk-orange
CYHb1-5	Sa-Dol	-	72	28	-	100	-	29.74	Yellow
CYHb1-4	C-Dol	10	82	8	7	87	6	7.04	Orange
DKHb1-1	Dol	-	89	11	-	75	25	9.89	Red-orange
DKHb2-2	C-Dol	8	88	4	33	67	-	4.67	Orange
DKHb2-1A	Dol	T	96	4	50	-	50	5.77	Yel-orange
DKHb2-1B	Dol	1	90	9	-	100	-	32.58	Red-orange
MRHb1-3	C-Dol	37	61	2	66	34	-	5.80	Orange
MRHb1-2	Dol	7	91	2	27	73	-	4.31	Yellow
MRHb1-2	Geodes	73	26	1	-	-	-	-	-
MRHb1-1	Dol	7	91	2	10	90	-	3.32	Orange
CHHb1-1	C-Dol	29	68	3	47	53	-	2.46	Yellow-or
PEARL SHALE MEMBER									
WSWe1-1	Dol-Sh	-	-	-	10	90	-	-	-
RLWe1-3	Dol-Sh	6	40	54	-	100	-	-	-
CYWe1-7	Sh-Dol	1	66	33	2	98	-	35.86	Orange
CYWe1-6	Cal-Sh	7	-	93	-	-	100	79.51	Brown
CYWe2-2	Sh-Ls	76	-	24	100	-	-	32.95	Yellow
DKWe2-2	Sh-Dol	1	73	26	-	90	10	40.21	Orange
MRWe1-5	Dol-Ls	79	12	9	95	5	-	11.22	Orange
CHWe1-1	Ls-Sh	-	-	-	45	10	45	-	-
WOLFCAMP SERIES - NOLANS FORMATION									
Herington Member									
WSHe1-7	Dol	-	94	6	-	94	6	13.49	Yellow
WSHe1-6	Dol	-	92	8	-	100	-	8.83	Dk-yellow
WSHe1-5	Si-Dol	2	68	30	-	96	4	17.51	Dk-orange

Table 3 (Cont.).

Geologic section	Lithology	Powder sample			Colloidal fraction			Insoluble residue percentage	Filtrate color
		Cal-cite	Dolo-mite	Quartz	Cal-cite	Dolo-mite	Quartz		
WSHe1-4	Dol	-	92	8	-	98	2	10.22	Orange
WSHe1-3	Dol-Sh	-	-	-	-	100	-	-	-
WSHe1-2	Dol	6	83	11	3	89	8	12.03	Orange
WSHe1-1	Dol	-	96	4	-	100	-	9.57	Yellow
RLHe2-5	Dol	-	89	11	3	63	34	25.54	Yel-orange
RLHe2-4	Sh-Dol-Ls	49	21	30	46	54	-	40.38	Li-orange
RLHe2-3	C-Dol	14	82	4	7	88	5	13.99	Dk-yellow
RLHe2-2	Sh-Dol-Ls	42	11	47	18	47	35	38.79	Orange
RLHe2-1	Dol	-	89	11	3	61	36	24.53	Red-orange
RLHe1-4	Dol	2	92	6	13	80	7	4.22	Red-orange
RLHe1-3	Dol	-	87	13	12	75	13	25.03	Red-brown
RLHe1-2	Dol	1	95	4	-	74	26	10.15	Li-yellow
RLHe1-1	Sh-Dol	1	77	22	2	8	90	40.17	Dk-orange
DKHe2-5	Dol	7	91	2	7	75	18	5.16	Li-yellow
DKHe2-4	Dol	-	94	6	8	70	22	10.10	Li-yellow
DKHe2-3	Dol	-	93	7	-	73	27	12.66	Orange
DKHe2-2	Dol	2	91	7	1	86	13	10.66	Li-yellow
DKHe2-1	Si-Dol	-	88	12	-	58	42	15.66	Li-orange
DKHe1-3	Dol	1	92	7	-	91	9	6.25	Li-orange
DKHe1-2	Si-Dol	1	89	10	-	50	50	17.38	Yellow
DKHe1-1	Si-Dol	-	87	13	-	34	66	12.29	Li-yellow
MRHe1-2	Dol	6	92	2	21	79	-	4.11	Oran-brown
MRHe1-1	Dol	-	98	2	5	95	-	5.15	Orange
MRHe2-2	Dol	2	95	3	3	97	-	7.19	Yellow
MRHe2-1	Dol-Ls	57	40	3	83	9	8	2.42	Dk-yellow
CHHe1-6	Dol	3	89	8	-	77	23	8.00	Yellow
CHHe1-5	Dol	1	90	9	6	44	50	11.99	Yellow

Table 3 (Cont.).

Geologic section	Lithology	Powder sample			Colloidal fraction			Insoluble residue percentage	Filtrate color
		Cal-cite	Dolo-mite	Quartz	Cal-cite	Dolo-mite	Quartz		
CHHel-4	Ch-Dol-Ls	63	28	9	74	7	19	38.53	Orange
CHHel-3	Dol-Sh	-	87	13	6	57	37	42.25	Orange
CHHel-2	Dol-Ls	79	12	9	86	14	-	6.58	Orange
CHHel-1	Si-Dol	-	89	11	9	51	40	22.88	Li-yellow
MNHel-14	Dol	2	95	3	17	81	2	4.18	Red-orange
MNHel-13	Dol	1	95	4	6	94	-	8.04	Yellow
MNHel-12	Dol	2	92	6	9	91	-	8.22	Brown
MNHel-11	Dol	1	94	5	5	47	53	4.26	Orange
MNHel-9	Dol	1	94	5	5	28	72	8.80	Li-orange
MNHel-8	Dol	-	90	10	12	33	55	23.46	Yellow
MNHel-6	Dol	-	90	10	5	90	5	16.34	Yellow
MNHel-3	Dol	-	89	11	-	100	-	13.70	Orange
MNHel-1	Dol	3	90	7	40	40	20	17.65	Li-orange
Paddock Shale Member									
MRPal-2	Dol-Sh	-	84	16	-	72	28	25.66	Red-orange
MRPa2-3	Dol-Sh	-	54	46	-	-	100	-	-
CHPal-1	Sh-Dol	-	78	22	9	25	66	29.20	Orange
KRIDER LIMESTONE MEMBER									
RLKrl-1	Dol	2	89	9	-	33	67	15.94	Li-yellow
MRKrl-3	Dol-Ls	84	10	6	98	-	2	14.56	Yellow
MRKrl-2	Ls-Dol-Sh	36	28	36	57	43	-	-	-
MRKrl-1	MLs	90	4	6	100	-	-	11.09	Yellow
WINFIELD FORMATION									
CRESSWELL LIMESTONE MEMBER									
RLCrl-2	Si-Ls	83	3	14	100	-	-	14.50	Yellow
RLCrl-1	Si-Ls	82	2	16	89	-	10	15.60	Yellow

Table 3 (Cont.).

Geologic section	Lithology	Powder sample			Colloidal fraction			Insoluble residue percentages	Filtrate color
		Cal-cite	Dolo-mite	Quartz	Cal-cite	Dolo-mite	Quartz		
DKCr1-2	Si-Dol	–	90	10	2	88	10	12.61	Red-brown
DKCr1-1	Ch-Dol	2	82	16	1	56	43	15.32	Orange
DKCr2-5	Dol-Ls	70	23	7	84	11	5	14.89	Yellow
DKCr2-4	Dol-Ls	56	39	5	68	16	16	14.70	Yellow
DKCr2-3	Si-Ls	84	2	14	87	–	13	14.01	Orange
DKCr2-2	Si-Ls	85	4	11	81	–	19	14.52	Li-yellow
DKCr2-1	Ch-Ls	88	–	12	86	–	14	12.86	Orange
GRANT SHALE MEMBER									
RLGr1-3	Ls-Sh	72	5	23	31	58	11	30.93	Yellow
RLGr1-2	Ls-Sh	–	–	–	50	–	50	–	–
RLGr1-1	Ls-Sh	–	–	–	50	–	50	–	–
DKGr1-3	Dol-Sh	6	69	25	–	75	25	–	–
DKGr1-2	Dol-Sh	–	79	21	–	57	43	–	–
DKGr1-1	Dol-Sh	–	68	32	–	60	60	–	–
DKGr2-1	Sh-Dol-Ls	55	23	22	42	–	58	35.86	Yellow
STOVALL LIMESTONE MEMBER									
RLSt1-2	Ch-Ls	86	1	13	83	3	14	34.34	Dk-yellow
RLSt1-1	Ls	91	2	7	100	–	–	18.50	Yellow
DKSt1-1	Ch-Dol	1	32	67	–	32	68	23.83	Oran-brown
CHSt1-3	Ch-Ls	85	6	9	90	–	10	9.63	Li-orange
CHSt1-2	Ch-band	20	5	75	42	10	48	82.79	Yellow
CHSt1-1	Ch-Ls	74	3	23	92	–	8	22.84	White

Table 3 (Cont.).

Geologic section	Lithology	Powder sample			Colloidal fraction			Insoluble residue percentages	Filtrate color
		Cal-cite	Dolo-mite	Quartz	Cal-cite	Dolo-mite	Quartz		
DOYLE FORMATION									
GAGE SHALE MEMBER									
DKGgl-1	Dol-Sh	-	71	29	-	75	25	-	-
CHGgl-6	Ls-Sh	66	-	34	55	-	45	49.88	Orange
CHGgl-5	Ls-Sh	-	-	-	50	-	50	-	-
CHGgl-4	Dol	4	93	3	4	92	4	8.12	Orange
CHGgl-3	Ls-Sh	-	-	-	100	-	-	-	-
CHGgl-2	Ls-Sh	-	-	-	100	-	-	-	-
CHGgl-1	Ls-Sh	-	-	-	100	-	-	-	-
TOWANDA LIMESTONE MEMBER									
RLTol-3	Ls	90	3	7	100	-	-	5.70	Yellow
RLTol-2	Ls	93	-	7	99	-	1	9.12	Yel-orange
RLTol-1	Ls	94	-	6	91	9	-	5.25	Yellow
CHTol-5	MLs	90	6	4	100	-	-	1.36	Yellow
CHTol-3	Ls	96	2	2	100	-	-	4.92	Yellow
CHTol-2	Ls	94	3	3	100	-	-	3.30	Li-orange
CHTol-1	Ls	95	-	5	90	10	-	9.15	Red
BUTol-2	Si-Dol	2	86	12	16	84	-	6.55	Red-orange
BUTol-1	Dol	8	88	4	90	-	10	3.49	Orange
BUTo2-1	Si-Dol	-	73	27	26	74	-	15.88	Li-orange
HOLMESVILLE SHALE MEMBER									
RLHvl-4	Sh-Ls	73	1	26	100	-	-	25.12	Orange
CHHvl-2	MLs	90	5	5	95	5	-	8.97	Orange
BUHvl-1	Sh-Dol	-	83	17	-	-	-	26.16	Red-orange

Table 3 (Concl.).

Geologic section	Lithology	Powder sample			Colloidal fraction			Insoluble residue percentages	Filtrate color
		Cal-cite	Dolo-mite	Quartz	Cal-cite	Dolo-mite	Quartz		
BARNESTON FORMATION									
FORT RILEY MEMBER									
CHFr2-2	Dol	-	83	17	-	100	-	21.24	Orange
CHFR1-10	Dol	-	88	12	6	94	-	11.19	Li-orange
CHFr1-9	Si-Dol	8	74	18	27	73	-	14.62	Yellow
CHFr1-8	Si-Dol-Ls	65	18	17	88	12	-	13.78	Orange
CHFr1-7	Dol	1	89	10	1	89	10	16.37	Li-yellow
CHFr1-6	Dol	2	80	18	2	91	7	18.54	Yellow
CHFr1-5	Dol-Sh	-	-	-	8	92	-	-	-
CHFr1-4	Dol	-	91	9	5	84	11	16.31	Yellow
CHFr1-3	Dol-Sh	-	-	-	4	60	36	-	-
CHFr1-2	Dol-Sh	-	-	-	-	55	45	-	-
CHFr1-1	Dol	3	91	6	9	91	-	17.05	Li-orange

with reference to the Pearl shale. The illite varies locally very little but greatly from section to section, much as it does in the Pearl shale.

The greatest difference in clay mineralogy is not in the mineral constituents but in the crystallinity of those constituents. The well crystalline montmorillonite-chlorite interlayers of the Pearl shale have been changed to montmorillonite-vermiculite. The high degree of regularity of interstratification has become more irregular with the decrease in crystalline state. The chlorite of both free and interlayered states are iron-rich poorly crystalline and often show a trend toward a vermiculite (see Table 2). In Washington County, the chlorite was placed in Class 4, which denotes a chlorite-vermiculite border transition toward vermiculite. The chlorite in the Morris County samples is characteristic of Class 5 which is surprising since the Morris County Wellington chlorite was iron rich poorly crystalline. A feasible explanation is that the Wellington samples were taken at the erosional edge of its extreme eastern outcrop in Kansas, whereas the Herington samples, even though weathered, are located farther west of its respective erosional boundary. Both Herington samples from Morris County were collected from roadcuts on the tops of hills.

The most unusual section of Herington was encountered in Chase County in which one bed contained visible chert nodules underlain by a foot of shale containing cauliflower geodes filled completely with pink-colored quartz. In general, the clay mineralogy of the Chase section is the same as the overlying Wellington

shale with a prevalence of montmorillonite-vermiculite and mont-morillonite-swelling vermiculite being present. The chert was found in the middle member, CHHel-4, and the shale, CHHel-3, contained the geodes. Under this shale is a very hard orange and black mottled magnesian limestone which contains only poorly crystalline iron-rich illite and free montmorillonite. This assemblage seems to be an anomaly since the basal member of the Herington mineralogically conforms to the interlayer complex of the upper part of the section. The clay mineralogy trends in the Herington are as follows:

1. Similar illite percentage relationships in Washington, Riley, and Marion counties. A different set of percentage values in Dickinson, Morris, and Chase counties, the latter being 10 to 20 per cent lower.

2. A general concentration of interlayered clay minerals in the lower parts of each section, except in Chase County where interlayering shows continuous vertical extent.

3. Less chlorite in interlayer complexes and more vermiculite especially in Dickinson and Chase counties.

4. Interlayers are more randomly interstratified than in the Wellington and superlattice structures are generally lacking. This condition compares favorably with the description of the Hollenberg.

5. The Washington and Marion counties have sections which appear to be very similar in both clay and carbonate mineralogy.

The Herington is a dolomite with the exception of samples

CHHel-2, MRHe2-1, and CHHel-4. The shale partings, RLHe2-2 and RLHe2-4, show a definite increase in calcite as does the included calcitic dolomite, RLHe2-3. In Morris, Dickinson, and Chase counties there is an increase in calcite in the colloidal fraction. Another trend is that the Herington has a high silica content which increases in the colloidal fraction.

The insoluble residue percentages are variable as reference to Fig. 3 in the Appendix shows. These percentages indicate that the Herington grades from a highly impure carbonate rock such as RLHe2-5 in Riley County to a hard crystalline dolomite in Marion and Washington counties. The insoluble residue percentages of the Marion County section show lower values in the deeply weathered top of the section, and much higher percentages in the lower part of the section where visible weathering was not as pronounced. The insoluble residue percentages correlate somewhat with the colloidal silica percentages. This correlation indicates the insoluble residue quantity is a function in part of silification rather than an abundance or lack of detrital constituents. This phenomenon is exemplified by inspection of samples RLHe2-5, RLHe2-1, DKHe2-2, DKHe2-1, and CHHel-6 to 1-1. Further evidence was that the silica rich samples were often found to have a low clay percentage. The color of the filtrate was often red to orange where the insoluble residue was low. This would seem to indicate that goethite and low insoluble residue values in soft dolomites are correlative with extensive exposure to subaerial weathering.

Paddock Shale

The Paddock shale member of the Nolans formation was sampled in most places in contact with the base of the Herington. This shale is characterized by having very little evidence of lamination. The shale is often calcareous or dolomitic and shows an increase in carbonate minerals toward the contact with the Herington. This shale fractures into large conchoidally-shaped blocks rather than along well defined bedding planes. The color of the shale is consistently gray to gray green with black splotches of random dimensional orientation present. Numerous calcareous geodes were found and minutely crystalline calcite has formed boxworks along the fractures and joint patterns of the area.

The clay mineralogy is much the same as that found in the Herington dolomites. A distinct difference was found to exist in the distribution of chlorite and vermiculite; whereas the chlorite was definitely vermiculitic in the Herington, the Paddock chlorite was classed as being better crystalline or equal to that of Class 4. Regardless of the state of crystallinity, the iron-rich characteristics still prevail. This higher degree of crystallinity compares closely with that found in the Wellington shale. The most important difference between the mineralogy of the Wellington and that of the Paddock is the Paddock contains more free chlorite.

Analogous to this condition is the fact that the Paddock is less dolomitic than the Wellington shale. The author believes this

is due to an incipient relationship between abundant chlorite and less dolomite, and, conversely, less chlorite, more dolomite. This explanation follows the theory proposed by Zen (1959) which implied that dolomite could form by chemical transference of magnesium freed during the degradation process of chlorite in an environment of calcium carbonate. Where the Paddock is badly weathered as it was in Marion County, chlorite diffraction maxima reflect two phases, chlorite-montmorillonite and vermiculite-montmorillonite. Only in Chase County was a montmorillonite-swelling vermiculite superlattice found but this is not really surprising since this county evidently reflects a localized depositional and weathering environment allied to the paleogeographic and structural trends in this area of Kansas.

Krider Limestone

The Krider limestone member of the Nolans formation was only sampled at two locations. One was in Riley County and the other in western Morris County, where it was collected in sequence with the rest of the Nolans formation. The rock varies from a soft, clayey single-bedded dolomite in western Riley County to a two-bedded unit in Morris County, the upper being a hard dolomitic limestone and the lower a hard crystalline magnesian limestone. The beds are separated by a dolomitic shale break. The sample from Riley County has a lower percentage of illite than the overlying Paddock shale. The illite is generally well crystalline with only traces of illite-montmorillonite. The sharpness of the

montmorillonite-chlorite interlayer maxima indicate that the components are well crystalline. Heat treatments showed that the chlorite was characteristic of Class 6.

The clay mineralogy of the Krider in Morris County is much more complex. The prominent first order reflection of the random interlayer at 14A was found to be at 13.7A. This 13.7A spacing indicated that illite was possibly one of the interlayer constituents. By assumption from the periodicity of sequential higher order basal spacings, the author determined that the montmorillonite was equal in quantity to the vermiculite. The illite component comprised 14 per cent of the interlayer from the top unit and 8 per cent for the shale break (Table 2). The bottom limestone showed no trace of montmorillonite-vermiculite-illite interlayer. All chlorite was identified as iron-rich poorly crystalline. Only small amounts of free chlorite and no free montmorillonite was identified.

The insoluble residue percentages for the three carbonate units ranged from 11 to 16 per cent. The sample from Riley County contained the highest per cent of acid insoluble constituents. All filtrate colors from the Krider were yellow, indicating that the content of soluble iron compounds was low.

Odell Shale Formation

The Odell shale in Kansas comprises 20 to 40 feet of shale section, most of which forms a poor outcrop. Five samples from three counties were collected in order to give some indication

of the clay mineral changes between the Krider and Cresswell
limestone members.

Sample RLOdl-1 was from the shale contact with the Krider
dolomite in Riley County. The percentage results are shown in
Table 2. About 20 per cent of the sample was composed of random
to regular interlayered chlorite-montmorillonite. Three diffrac-
tion maxima on the same base reflection of this chlorite-mont-
morillonite showed all interlayered gradations between free
chlorite and free montmorillonite. The chlorites in both the
free and interlayered states are well crystalline. The lower
sample from a red shale in Morris County, MROdl-1, contained 16
per cent of randomly interstratified montmorillonite and Class 4
chlorite. All other samples are best described as illite shales
as this clay mineral makes up 96 per cent or more of the clay
fraction. All of the illites in the Odell shale are well cry-
stalline. Small amounts of iron-rich poorly crystalline chlorite
were found in the Dickinson County samples. Samples RLOdl-1 and
DKOdl-1 have colloidal dolomite and MROdl-2 has traces of col-
loidal calcite.

<p align="center">Cresswell Limestone</p>

The Cresswell limestone member is the top unit of the Win-
field formation. The author collected the Cresswell samples at
three locations, one in western Riley County and the other two
at the northern and southern ends of Dickinson County. In all
three sections, the Cresswell could be divided into two distinct

units--a lower massive bed often containing nodular chert and a
series of upper platy beds. The latter is often referred to as
the Luta limestone.

Of all the units studied, the Cresswell seems to have the
most constant clay mineral assemblage, both mineralogically and
percentage-wise. The illite, with the exception of DKCr2-5, is
well crystalline and varies in amount between 68 and 80 per cent.
Free chlorite varies in both percentage and crystallinity. The
highest percentage of chlorite occurred in Dickinson County in
samples DKCr1-1, DKCr1-2, and DKCr2-3. Chlorite peak ratio cal-
culations showed that all of the chlorite exhibited iron-rich
characteristics and was generally poorly crystalline. Where this
ratio became greater than unity, the author assumed the chlorite
was more of the character of vermiculite. Heat treatments to
450 degrees Centigrade revealed a collapse of every peak con-
nected with either chlorite or vermiculite, identifying the
Class as 1, 3, or 4.

Table 2 shows that montmorillonite-chlorite and montmoril-
lonite-vermiculite comprise the bulk of the interlayer clay. The
montmorillonite-vermiculite interlayer is random in Riley County.
In northern Dickinson County, the interlayer is montmorillonite-
chlorite and is random, and in southern Dickinson County the in-
terlayer becomes a regular or nearly regular interstratification
of montmorillonite-vermiculite with some chlorite interlayering
in samples DKCr2-3 and DKCr2-4. Traces of randomly interlayered
illite-montmorillonite were identified in all of the samples and
free montmorillonite was found to be absent.

The singular characteristic of the Cresswell limestone is its highly siliceous nature. The Riley County samples are siliceous dolomites. The section in southern Dickinson County ranges lithologically from a dolomitic limestone at the top of the section to a massive cherty limestone at the bottom. This lower zone contains chert nodules which are more or less circular in cross section and up to four inches in diameter. The chert is a dense material and is gray to black. The section in northern Dickinson County is a siliceous dolomite with the lower massive zone containing many chert nodules. The insoluble residue percentages are remarkably consistent and can be correlated as the maximum range of variation is around three per cent.

Grant Shale

The Grant shale member of the Winfield formation was sampled in Riley, Dickinson, and Butler counties. Samples were taken at the top, middle, and bottom of the section since this shale has a homogeneous lithology. The Riley and Dickinson County sections were very similar in clay mineralogy and percentage-wise very similar to the overlying Cresswell member. The illite percentage ranged from 70 to 80 per cent except for sample DKGr2-1 where the percentage dropped to 61. This particular sample was collected at the base of the Cresswell limestone in southern Dickinson County. The limestone zone of the Cresswell had abundant chert.

The clay suspension from the shale, DKGr2-1, and the overlying limestone were treated with 1N KOH solution to determine

whether the interlayer montmorillonite was of mica or volcanic derivation. The montmorillonite component of the interlayer adsorbed potassium and collapsed to a basal spacing to 10A, indicating the clay was derived from mica. The Grant shale displayed highly developed regular interlayering of montmorillonite-chlorite, whereas most of the interlayers in the Cresswell were random montmorillonite-vermiculite. Unlike the Wellington shale, the Grant generally has well crystalline free chlorite. The sample BUGr1-1 from Butler County had about 90 per cent illite and a corresponding decrease in montmorillonite-chlorite. The carbonate in the Grant was identified as either dolomite or calcite corresponding to the carbonate in the overlying Cresswell.

Stovall Limestone

The Stovall limestone member of the Winfield formation is a limestone in Chase and Riley counties and changes to a dolomite in northern Dickinson County. In Riley County, the Stovall is composed of two massive beds, the upper unit containing chert. Illite is the dominant clay mineral and is well crystalline in the chert bearing zone and poorly crystalline iron-rich in the lower unit. The free chlorite is poorly crystalline. The lower zone contains some regularly interstratified montmorillonite-chlorite while montmorillonite-vermiculite was found in the upper part. In Dickinson County, the single-bedded cherty dolomite correlates in terms of interlayering with the non-cherty zone in Riley County.

The section in Chase County has two beds, both containing nodular chert, and are separated by a chert band. The illite percentages are low in the cherty limestones and range up to 90 per cent in the chert band. The chlorite is generally iron-rich poorly crystalline, and free montmorillonite was found.

Gage Shale

The Gage shale has essentially the same clay mineralogy as the Grant shale in Riley, Dickinson, and Butler counties. Illite is the major clay constituent but montmorillonite-chlorite comprises up to 20 per cent of the clay fraction. The chlorite in the interlayer is generally well crystalline as it was in the Grant shale.

The Gage shale in Chase County was taken from the Gage-Stovall contact and to a depth of 15 feet below. In this section the major clay mineral was illite except for sample CHGgl-6, which was unusually high in montmorillonite. All samples of the shale had colloidal calcite, while CHGgl-4 was a dolomite. This dolomite had a low insoluble residue of eight per cent. The clay mineralogy of the dolomite showed illite and montmorillonite in the free state with little interlayered clay present.

Towanda Limestone

The Towanda limestone member of the Doyle shale formation is characterized by a dominant percentage of illite, a relatively

high percentage of free montmorillonite, a dominancy of vermicu-
lite over chlorite, and a near absence of interlayered clays.
The only interlayered clays found were traces of random illite-
montmorillonite, illite-chlorite, and vermiculite-chlorite. The
comparison of this rather simple clay mineral assemblage with
the highly complex interlayered clays of the overlying Gage shale
member seems to indicate a major clay mineralogical break. As
was stated above, the Gage shale shows an interlayer complex of
chlorite-montmorillonite corresponding to the strata above it.
The fact that these two are members of the same formation is
most remarkable.

The Towanda member was found to be a series of hard platy
limestone beds in Riley and Chase counties and a siliceous dolo-
mite in Butler County. Insoluble residue percentages are very
low (Table 3). The highest values are those in Butler County.
The only sample to show a remarkable difference in lithology was
CHTol-1 which had the appearance of an interformational breccia.
This rock is composed of angular fragments of iron-stained lime-
stone and green shale. The limestone has the appearance of
CHTol-2 and the lithology of the shale portion is similar to
CHHv2-3 which underlies it. Sample CHTol-1 is the only unit in
the section to have more than a trace of free chlorite. With the
exception of Butler County, very little quartz was found.

Holmesville Shale

The Holmesville shale member of the Doyle formation has the

same clay mineral assemblage as the Towanda limestone. In Riley County, poorly crystalline illite predominates, whereas in Chase and Butler counties the illite is well crystalline with some zones showing transitional and iron-rich stages. The only noticeable difference in clay mineralogy is the occurrence of free montmorillonite being limited primarily to the top of the section where weathering is most pronounced. In the Towanda, the vertical distribution of montmorillonite was continuous. The chlorite in the Holmesville is almost without exception poorly crystalline. Much of the chlorite in Riley County is iron-free. Sample RLHvl-4 is correlative with sample CHTol-1 but even though the brecciated appearance is essentially the same, there is a distinct trend toward shalyness. This can be visualized by comparison of the insoluble residue. Sample CHTol-1 has about nine per cent as compared to about 25 per cent for RLHvl-4. CHHvl-2 is a limestone which is primarily composed of calcite geodes. The clay mineralogy, however, is the same as that of the shale.

Fort Riley Limestone

The Fort Riley member of the Barneston formation was sampled at one location. This sample was taken from the upper ten feet of the member in a quarry site in southern Chase County. Illite was the major clay mineral and was iron-rich well crystalline. Chlorite was present in small amounts and varied in crystallinity from iron-rich poorly crystalline to Class 5 crystallinity. The upper part of the section contained small amounts of regularly

interlayered chlorite-vermiculite. All samples contained some vermiculite. The insoluble residue percentages of the Fort Riley displayed the shaly nature of the rock. The values averaged about 15 per cent. All of the rock was a dolomite except CHFrl-8, which was a secondary limestone.

DISCUSSION ON CLAY MINERAL GENESIS

The clay mineral genesis of the investigated area reflects the influence of many factors. The most important of these are: (1) Relationships of depositional environments to regional structure; (2) the effects of substitutional exchange ions as agents of post-depositional clay alteration; (3) the pH or hydrogen ion potential activity in the various sites of clay mineral deposition; (4) the state of aggradation or degradation which the clay mineral was in at the time of deposition; (5) subaerial and subaqueous weathering processes imposed on the clay mineral groups either at the present time or in the geologic past; and (6) the variations in porosity between the limestones, dolomites, and shales of which the clays are major or minor components.

North and East Central Kansas can be divided into five general areas on the basis of regional structure (Fig. 1 in the Appendix). All the samples collected in Chase County were from locations on the eastern flank of the Nemaha Ridge and on the northwestern margin of the Oklahoma Platform. In Riley County, the depression between the Nemaha Ridge and the Abilene anticline is locally known as the Irving syncline. To the west of the

Abilene anticline is the Salina Basin.

The samples from Washington County denote the strictly marine environment of the Salina Basin in that segment of Permian time. Illite has been said to form where the depositional rate is slow. Grim and Johns (1954), p. 101, reported that well crystalline chloritic clays were detrital in origin. An alkaline environment seems to favor the preservation of three layer clay minerals. These conditions apply ideally to the depositional sites of the Paddock shale, Herington limestone, Wellington shale, and Hollenberg limestone in Washington and Marion counties. The clay mineral assemblage is largely well crystalline illite and poorly crystalline chlorite. The chlorite has the properties of degraded chlorites which are essentially detrital skeletal aluminum silicate sheet structures. In the case of these chlorites, the bulk of the lattice vacancies have gradually become occupied by iron cations of both ferrous and ferric states. This indicates that these rocks have permitted the passage of solutions containing iron. The fact that the chlorite is still poorly crystalline is an indication that the formation of authigenic well crystalline chlorite has never really commenced. A few samples of Herington dolomite had chlorite which was somewhat more chloritic than vermiculitic.

Subaerial weathering processes have altered the illite and chlorite in three general ways:

1. The notable appearance of illite-montmorillonite random interlayers implies that an occasional water layer in the clay structure has developed in place of the potassium

leached from the illite. The presence of illite-mont-
morillonite is more noticeable in the dolomites of the
Hollenberg and Herington than in the associated Paddock
and Wellington shales. The best development of this type
of interlayer was found in samples WSHel-7, WSHel-5, and
WSHel-4, which contained numerous iron-stained geodes.
Zones in contact with the soil profile also contained
illite-montmorillonite interlayering.

2. The chlorite appears to be changing to montmoril-
lonite through an intermediary stage of vermiculite. The
change from chlorite to vermiculite could be accomplished
quite easily where the chlorite has experienced partial
loss of the brucite layer during transportation. The
chlorite which behaves as a vermiculite upon heating, as
described by Schultz (1958), would probably have at least
part of the brucite sheet absent. This condition is fur-
ther evidenced in sample WSHel-5 where chlorite approached
a regular interstratification with vermiculite. The next
alteration stage would then be the transformation of ver-
miculite to montmorillonite. This latter statement is in
part substantiated by the observation that the relative
vermiculite content and montmorillonite part of the clay
fraction counterbalance, indicating a transitional equili-
brium during extended weathering processes.

3. The presence of iron-rich chlorite and iron-rich
illite serves as evidence of subaerial weathering.
Evidence that weathering of the Washington County strata

hasbeen of shorter time extent can be substantiated by a comparison with a comparable section of Hollenberg dolomite and Pearl shale from the northwestern corner of Riley County. The clay mineral assemblages of the shale fluctuates in a regular cycle of percentages in a vertical direction throughout the section. When the samples RLWel-3 and RLWel-6 are compared with the slope of the local topography, a correlation between montmorillonite and the formation of terrace breaks can be made. This is probably due to recent weathering. The Riley County section has very little interlayered material present, which could mean that the change from degraded illite and degraded chlorite to montmorillonite has been by more direct alteration and the true vermiculitic stage has been quickly passed through. The percentages of chlorite in this section is constant from sample to sample. The true well crystalline chloritic nature of this mineral indicates a shorter transportation distance from the immediate source which was presumably the topographically higher expression of the Abilene anticline.

The Hollenberg clay mineralogy in Riley County holds the same environmental connotation as in Washington County. The shorter distance of transportation has had an effect on the illite crystallinity in that degradation has not been carried to the extent as it had in Washington County. The presence of iron containing solutions is evidenced by the fact that in the Herington of Washington County, the geodes are stained orange and brown, whereas the rock itself has a homogeneous gray color with no surficial indication of the iron content. The zones immediately

beneath the montmorillonite rich strata in the Wellington shale of Riley County are unique in that the illite is iron-rich. This condition may have arisen from the concentration of the iron in the impermeable layer of shale. Leaching would cause such a downward influx and subsequent concentration of iron containing solutions.

The Hollenberg sample, CYHb2-1, from Clay County, is a low insoluble residue dolomite in which weathering has leached almost everything away except a skeletal framework of pelecypods. The clay mineral assemblage is entirely that of illite and chlorite. Because this sample was taken from a similar geographical distance from the axis of the Abilene anticline as sample RLHb1-1, it is not surprising to find similar evidence of environmental conditions. The Hollenberg in central Dickinson County and western Morris County, although in a different basin of deposition, have the same evidence for marine clay mineral environment as the sections previously mentioned. The Wellington shale with the exception of the upper shale MRWel-6 has the same clay mineralogy as the northern sections. This situation has led the author to the conclusion that clay minerals deposited in similar basins of deposition will have the same environmental history. The only real factors causing appreciable change in clay mineralogy from one basin to another would be those of weathering and a source area of completely different lithology.

The section from the Paddock shale up through the Hollenberg dolomite in southern Clay County and northern Dickinson County is situated on the approximate axis of the Abilene

anticline. The clay mineral assemblages are characterized by interlayered complexes of tri-layered clay silicates with a high degree of regularity in the interstratification sequence (Plates X - XIV). In general, the shales are characterized by well crystalline montmorillonite interstratified with well crystalline chlorite. The dolomites of the Hollenberg and Herington have montmorillonite-vermiculite interstratifications. This diverse assemblage could be visualized as a composite concentrated deposit of the reworked sediments intimately associated with the immediate source area of the Abilene anticline. If this area represented an environment of brackish water as contrasted with the marine environment in the Salina Basin, a marked difference in clay mineralogy should be expected. The shales because of their lack of porosity should be a better index of paleomineralogic relations for the area.

Milne and Earley (1958) stated that the alteration of clay minerals in limestones is preferentially more severe than in the shales merely because of the porosity difference. Several things indicate a near shore or brackish water environment of deposition. One basis is that the illite constituent is present in abnormally low values, indicating a less stable environment for the preservation of three-layer silicates. The unusually high percentage of regularly and randomly interstratified clay minerals which exhibit all gradations in crystallinity could be interpreted as being weathered by-products of extremely reworked sediments. One sample, CYHbl-5, was examined under a binocular scope and was found to have well rounded grains of quartz.

Another thing that supports the brackish water theory is the presence of high percentages of interlayered montmorillonite usually involved in a superlattice structure with chlorite or vermiculite. The same samples show very little free chlorite and free montmorillonite is completely absent. All these conditions rather belie the formation of the interlayer by some recent weathering process.

Weaver (1956) suggested that much of the montmorillonite-chlorite interlayering was diagenetic. This is entirely possible if diagenesis is used in the sense of exchange ion adsorption after deposition and before lithification. The montmorillonite, in this case, would be the clay mineral originally deposited just as it is being deposited at the present time at the mouth of the Mississippi River. Diagenetic changes would only apply to the chlorite formation by the continued adsorption of magnesium ions into the water layer along with unattached hydroxyl groups. This process could replace every other water layer to form a regular mixed layer or might replace water layers randomly.

Finally, the blocky character of the Wellington and Paddock shale suggests a rapid change in salinity from acid to alkaline, causing a sudden flocculation of a majority of the particles in suspension. Assuming that the clays were poorly crystalline montmorillonites, degraded chlorites and illites, and vermiculites, all of whose skeletal structures carry a negative charge, an increase in concentration of hydronium ions (H_3O+) would also cause a floccing action.

EXPLANATION OF PLATE X

A variation diagram showing the clay mineral percentages of
the Hollenberg member of the Wellington formation as they relate
to the regional structure of the area from which the samples were
taken. Each section is plotted from top to bottom in a left to
right direction. The structures have been written in at the ap-
proximate positions at which they transect the sampled sections.
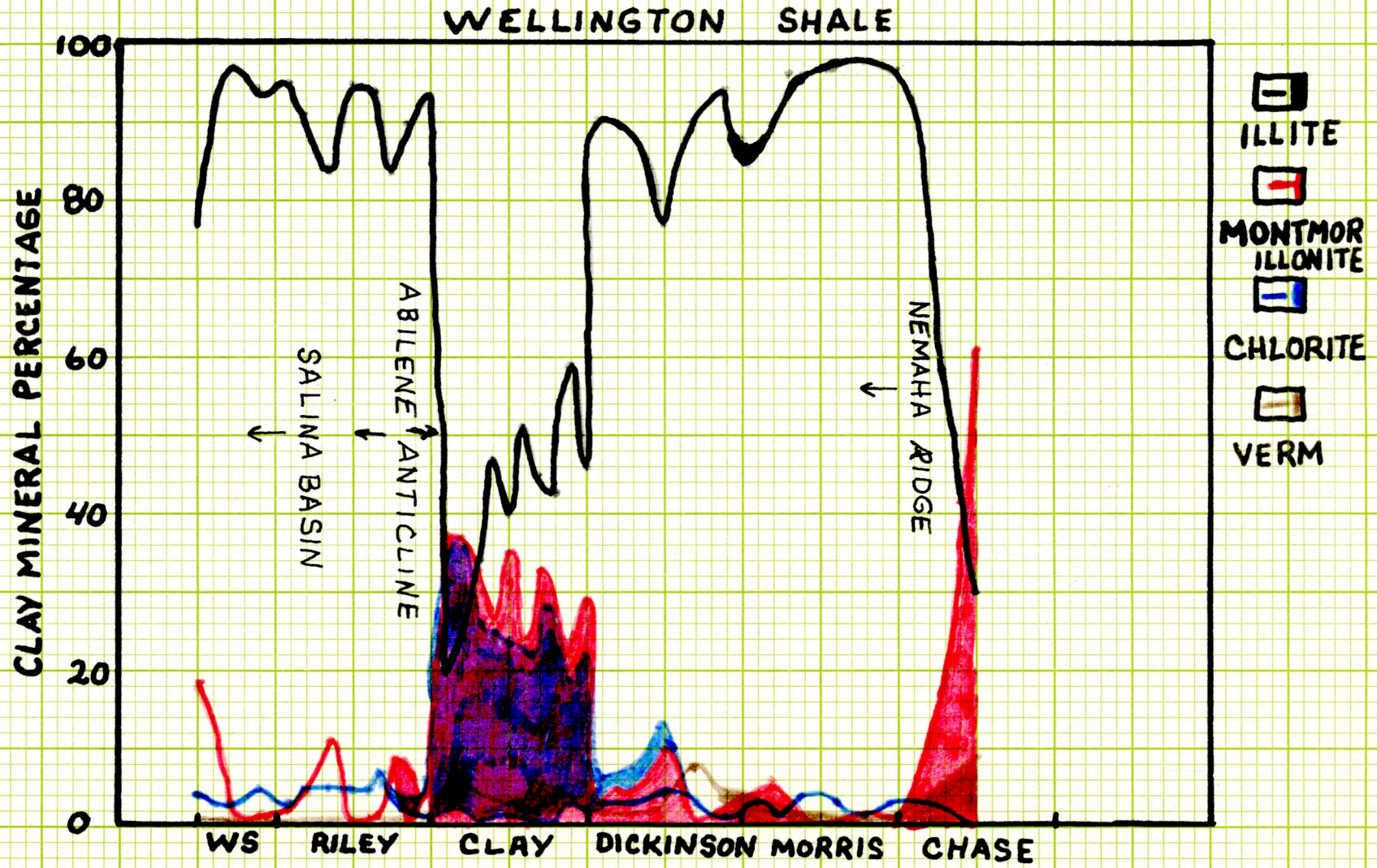The shaded areas under the curves represent the relative amount
of interlayered clay constituent.

PLATE X

HOLLENBERG DOLOMITE
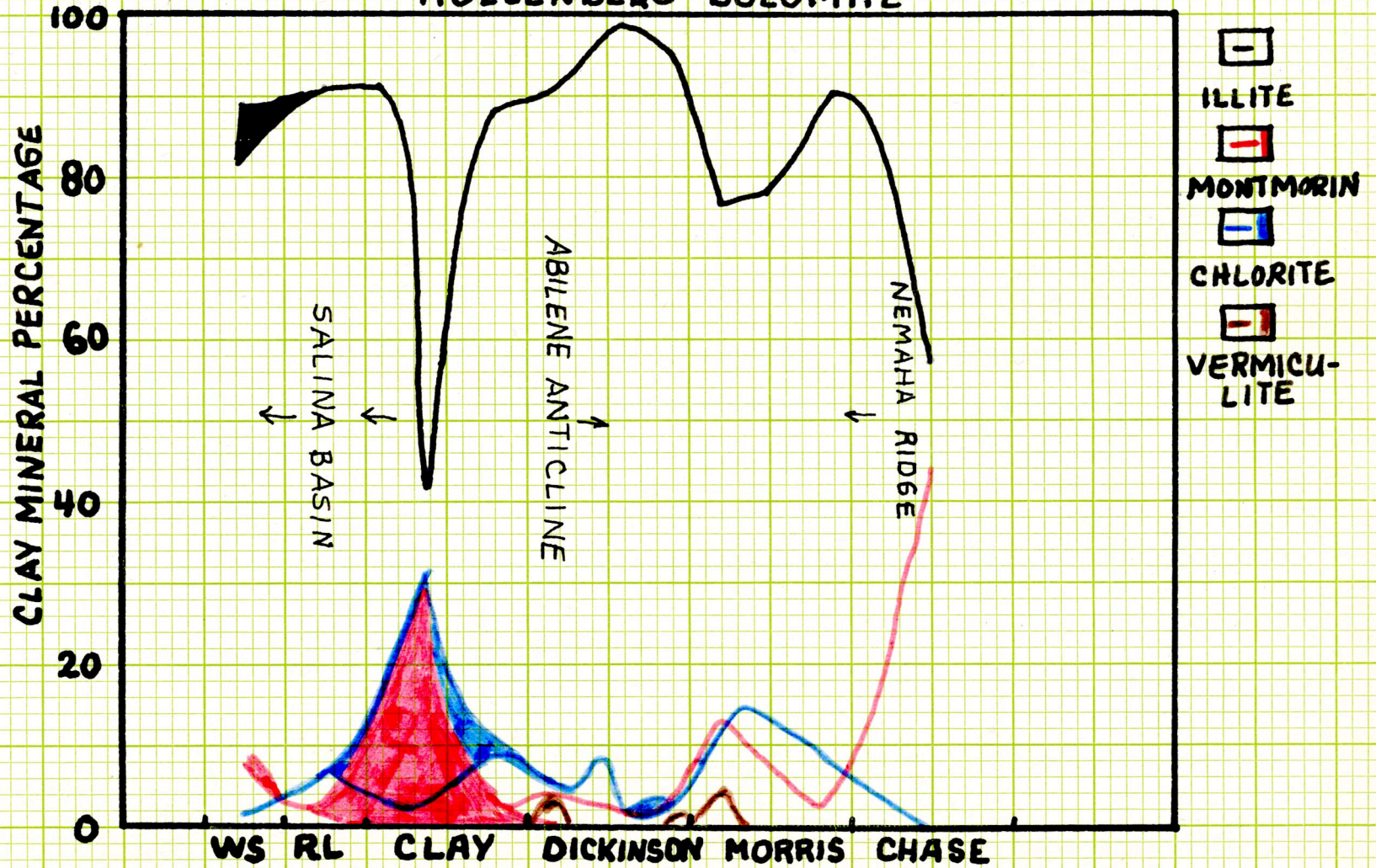
EXPLANATION OF PLATE XI

A variation diagram showing the relation of clay mineral percentages in the Pearl shale to the regional structure of the investigated area. Each section is given from top to bottom as left to right on the diagram. The structures have been written in at the approximate position of transection with the sampled sections. The shaded-in areas under the curve represent the amount on interlayered constituents.

PLATE XI

WELLINGTON SHALE

CLAY MINERAL PERCENTAGE

100
80
60
40
20
0

SALINA BASIN

ABILENE ANTICLINE

NEMAHA RIDGE

WS   RILEY   CLAY   DICKINSON MORRIS   CHASE

ILLITE

MONTMOR ILLONITE

CHLORITE

VERM

96

EXPLANATION OF PLATE XII

A variation diagram showing the clay mineral percentages as they relate to the regional structure of Kansas. This diagram is based on the percentages in the Herington member of the Nolans formation. The illite is in black, vermiculite in purple, montmorillonite in red, and chlorite in green.

PLATE XII

HERINGTON DOLOMITE

CLAY MINERAL PERCENTAGE

100
80
60
40
20
0

SALINA BASIN
ABILENE ANTICLINE
IRVING SYNCLINE
ABILENE ANTICLINE
NEMAHA RIDGE

WASHINGTON   RILEY   DICKINSON   MORRIS   MARION   CHASE

ILLITE
MONTMORIN
CHLORITE
VERMICU-LITE

96
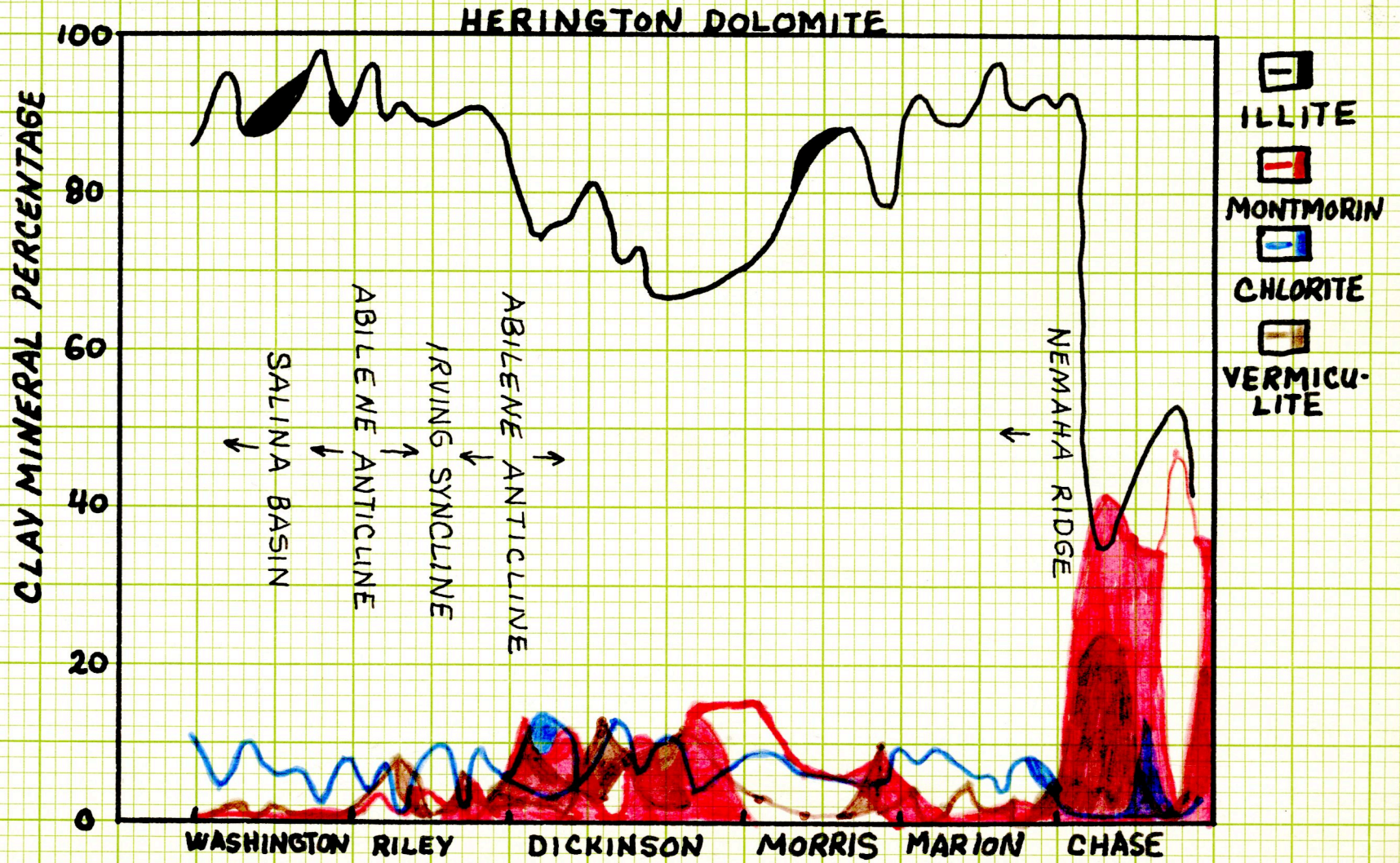
EXPLANATION OF PLATE XIII

A variation diagram of the clay mineral constituents of the
Paddock shale based on percentage determinations. The relative
positions of the regional structure are plotted at the approximate
place where they transect the sample locations. The shaded-in
areas under the curves correspond to the relative amounts of
interlayer montmorillonite-chlorite.

PLATE XIII

PADDOCK SHALE

ILLITE

MONTMORIN

CHLORITE

VERMICU-
LITE

CLAY MINERAL PERCENTAGE

SALINA BASIN

ABILENE ANTICLINE

IRVING SYNCLINE

ABILENE ANTICLINE

ABILENE ANTICLINE

NEMAHA RIDGE

WS   RILEY   DK   MORRIS   MARION   CHASE
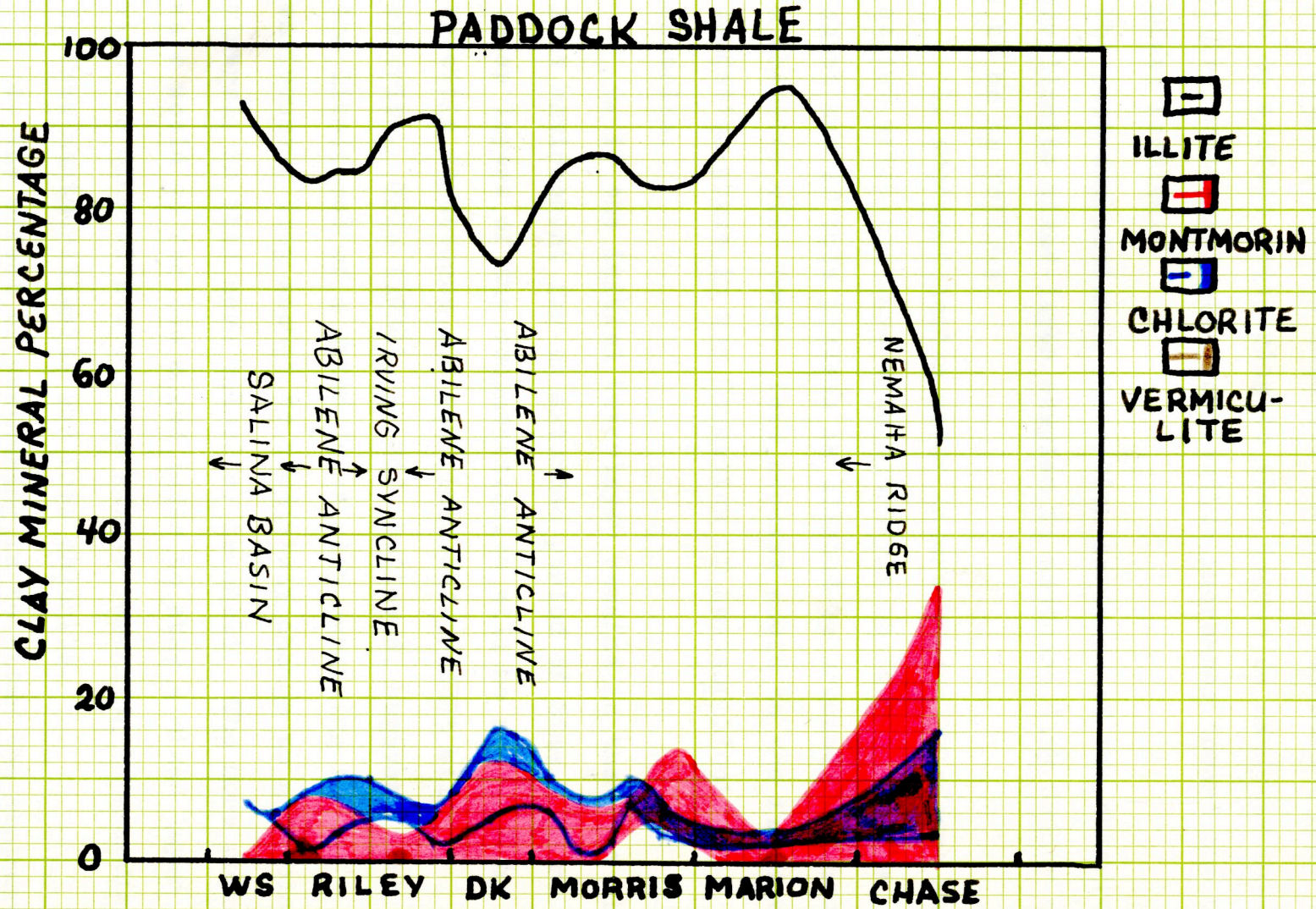
The montmorillonite-chlorite interlayer complexes have been altered by surface weathering to some degree as randomly interstratified montmorillonite-vermiculite increases toward the top of a given section.

The post-depositional alteration sequence of the chlorite-montmorillonite mixed-layer complex in southern Clay County appears to be as follows:

1. Montmorillonite water layers gradually adsorb magnesium which combines with hydroxyls to form a brucite sheet and if this process is allowed to proceed far enough, a chlorite will form. This process would be the first aggradation phase in the formation of montmorillonite-chlorite.

2. If the initial interlayer remains in the more alkaline environment for an extended period of time, other water layers of the montmorillonite will be replaced by brucitic structures and the final end-product will be chlorite. Grim (1958), p. 249, believed, however, that the likelihood of a mixed-layer clay remaining in one environment long enough to completely change to a stable mineral, in this case chlorite, is small. The more common case would be for the mixed layer to stay a mixed layer with its mineral composition always remaining intermediate to free montmorillonite and free chlorite.

3. The effect of weathering is to alter the montmorillonite-chlorite to montmorillonite-vermiculite and then finally to montmorillonite if time allows this to be done.

The complete sequence would be chlorite-vermiculite-swelling vermiculite-montmorillonite. The reasons for swelling chlorites and vermiculites are not fully understood.

The Chase County samples of the Hollenberg, Wellington, Herington, and Paddock illustrate this weathering sequence. The major clay admixture is a montmorillonite-vermiculite-swelling vermiculite random interlayer complex. Some regularly interlayered montmorillonite-swelling vermiculite is present. The author contends that the same mechanics of interlayer formation took place in the Nemaha Ridge area as in the area of the Abilene anticline. The mineral assemblages indicate that the type of source materials for the interlayers were essentially the same as in southern Clay County. The differences in the present clay mineralogy seem to be due solely to weathering processes. These weathering effects can be traced by means of the chlorite-montmorillonite interlayer from the Paddock up through the Hollenberg. The upper Paddock shale has montmorillonite interlayered more or less regularly with vermiculitic chlorite. The Herington has a predominance of montmorillonite-vermiculite with some expanding vermiculite present. The next stage of alteration is found in the upper part of the Pearl shale where swelling vermiculite predominates over the vermiculite and the interlayer becomes more and more like a montmorillonite. The final stage of alteration is present in the Hollenberg dolomite where interlayering is absent and only poorly crystalline montmorillonite remains.

The illite shows somewhat an inverse relationship in that its quality of crystallinity decreases in the lower part of the section. This observation correlates with the crystallinity trend of the illite in southern Clay County. The rate of sedimentation in both places was evidently rather slow as is partially supported by the fact that the local dip of the strata is gentle. A study of complete intervals of the Wellington shale in this area and in Clay County would probably reveal whether the brackish water environment was persistent throughout the entire time of deposition. Any change in clay mineralogy toward dominant illite and chlorite would indicate times of marine deposition.

The section from the Gage shale up through the Krider limestone in Riley and northern Dickinson counties displays the same montmorillonite-chlorite interlayering found in the Paddock shale. It must be noted, however, that the percentage of montmorillonite-chlorite interlayering decreases in this part of the section. The Gage shale in Butler County had more montmorillonite-chlorite than the others. This sample was taken very close to the axis of the Nemaha Ridge and was a compact brick red shale. In general, the shales are largely montmorillonite-chlorite interlayers and the clays in the limestones are montmorillonite-vermiculite. The general decrease in interlayered material was attributed to a pronounced change from brackish water conditions to those of the marine environment. This supposition is supported in part by the fact that the Odell, Grant, and Gage shales are clayey as contrasted with the silty shales

of the Paddock and Wellington. Another possibility is that the accumulation of interlayered clays had not progressed to the extent that they would predominate.

The limestones of the Cresswell and Stovall are noted for their abundance of chert. Comparison of clay mineralogy between these and the non-cherty limestones of the same formation show no apparent differences in clay mineralogy. Asmussen (1958) reported that montmorillonite in the cherty limestones were probably formed from the devitrification of volcanic ash. The Stovall and Cresswell show negligible amounts of free montmorillonite. Since the montmorillonite is interlayered with either chlorite or vermiculite, a mica derivation of the montmorillonite would seem more logical. Samples from chert-bearing limestones and associated shales were treated with 1N KOH to determine whether the interlayered montmorillonites were of volcanic derivation. In all cases, the basal spacing of the montmorillonite collapsed to 10A, indicating a mica derivation. Wilbur (1956) found that the presence of volcanic ash did not always correlate with either microscopic or visible chert.

The sampling location of the Krider limestone in Morris county was taken 30 miles from the axis of the Nemaha Ridge. The decrease in interlayer montmorillonite-chlorite which also has some random interstratification of illite indicates a trend toward marine conditions. This environment evidently has some ions of potassium as well as magnesium. In a transitional environment from brackish water to marine potassium fixation would be expected.

A major break in the vertical trend of clay mineralogy oc-
curs at the base of the Gage shale. The Towanda limestone,
Holmesville shale, and Fort Riley limestone are composed entirely
of illite, chlorite, and illite-chlorite interlayering. The pre-
dominance of these minerals and the lack of interlayered clays
is analogous to the clays in the Herington of Washington and
Marion counties where marine conditions evidently existed. The
hard, even texture of a black, lithographic limestone from the
Towanda in Chase County also indicates a slow rate of deposition.
The conditions along the axis of the Nemaha were evidently marine
during this period of deposition. Montmorillonite occurs in
sections which have been badly weathered.

Zen (1959) stated that possible relationships between cal-
cite-dolomite-quartz and the clay minerals could be derived. No
conclusive evidence could be found to support any visible rela-
tionship between clay mineralogy and carbonate mineralogy. The
Hollenberg and Herington rocks are dolomites, calcitic dolomites,
and a few limestones. The limestone was only found in the chert-
bearing Herington of Chase County. The frothy appearance of many
of these dolomites points to the possibility that this type of
dolomitization is secondary and would take place in a subaerial
weathering environment. The fact that poorly crystalline chlo-
rite was present in the dolomites could mean that the secondary
formation of dolomite is achieved by the adsorption of Mg++ from
the degradation of the chlorite. The limestones and even the
calcitic dolomites commonly had well crystalline chlorite.

McPherron (1956) proposed that the color of the shale was

an indication of the environment of the included clay minerals. The author found that no correlation could be derived between color of sediment and clay mineral composition. The Wellington is an alternating sequence of red, gray, gray-green, and green shales in Riley County, yet the clay mineral variations were small. However, the soluble iron content of the limestones and abundance of goethite can be used to indicate the weathered condition of the rock. The rocks containing poorly crystalline clay minerals, especially chlorite and montmorillonite, were also found to have an abundance of goethite.

SUMMARY OF CONCLUSIONS

The clay mineralogy of the upper Chase Group and lower Sumner Group is a result of alternating marine and brackish water conditions. The general trend is for a predominance of marine deposition in the lower part of the section, i.e., the Towanda, Holmesville, and Fort Riley, and an alternation of brackish and marine conditions in the upper part. There was no indication of an abrupt change in clay mineralogy along the Wolfcamp Leonardian time boundary. At the end of Wolfcamp time only the Salina Basin and the basin separating the Nemaha Ridge and the Central Kansas Uplift were definitely marine.

In general, the study of clay minerals indicates possible marine and brackish water environments when the effects of subsequent subaerial weathering are understood. The best evidence of weathering seemed to be the persistence of dolomite in rocks

subjected to long time surface exposure. Although dolomite seems
to have no intimate relationship genetically to the existing clay
mineral assemblages, the conditions necessary for the formation
of secondary dolomite, or dolomite formed by leaching of magne-
sium from chlorite when the latter degrades in the weathering
environment, parallel the alteration trends of the clay minerals
when subjected to weathering. Dolomite was thought to be form-
ing in the shales of the Wellington formation in this manner.

The presence of iron compounds soluble in HCl give a better
indication of the weathering extent in that the color of the so-
lution indicates the relative amount of oxidation of iron which
these rocks have undergone. The general color of the unweathered
rock is not an indication of the amount of iron or the composi-
tion of the clay mineral assemblages.

Regional structures appear to be the best indications as to
the locations of clay facies changes in an area. The study of
clay minerals in continuous lateral and vertical sequence from
the geographical position of the regional structure should indi-
cate differences in clay environments, rates of sedimentation,
and local disconformities.

Interlayer clays appear to be significant in the study of
post-depositional effects on clay minerals. Interlayered clay
transitions such as montmorillonite-chlorite were found to be
useful tools in determining the dominance of weathering and
environment.

The only major clay mineral hiatus occurred at the base of

Table 4. Summary of clay mineral alteration in the weathering environment.

Original Sediment	Weathering Stage		
	Slight	Intermediate	Late
Illite	Degraded Illite	Degraded Illite + Montmorillonite- Illite interlayer	Some iron rich illite, poorly crystalline montmorillonite major
Chlorite	Degraded Chlorite + Fe	Fe-rich Chlorite + Vermiculite + Chlorite-vermicuite interlayer	Vermiculite + Swelling vermiculite-montmorillonite interlayer
Chlorite-+ Montmorillonite (Regular)	Same (Random) M > C	Montmorillonite-Chlorite-Vermiculite (Random) M > V > C	Montmorillonite + Montmorillonite-Vermiculite- Swelling Vermiculite
Chlorite + Calcite	Chlorite, Calcite, and Dolomite Cal. > Dol.	Chlorite with leaching of Mg++ Dolomite > Calcite Leaching of Ca++	Poorly crystalline Fe++-rich Chlorite Montmorillonite, Dolomite dominant
Montmorillonite	Same	Same, poorly crystalline	Montmorillonite + K-fixated montmorillonite illite
Montmorillonite + Chlorite + Chlorite-montmorillonite + Swelling chlorite-montmorillonite + Calcite > Dolomite	Montmorillonite + Chlorite-Montmorillonite + Montmorillonite- Swelling Vermiculite + Dolomite > Calcite	Montmorillonite Vermiculite, Montmorillonite-Vermiculite M > V Dolomite major	
Chlorite in shales	Chlorite still well crystalline	Chlorite, poorly crystalline, + chlorite-vermiculite	Vermiculite + some montmorillonite + dolomite

the Gage shale.   This break seems to represent a major change
in environments in the Upper Wolfcamp strata from marine to
brackish water deposition.

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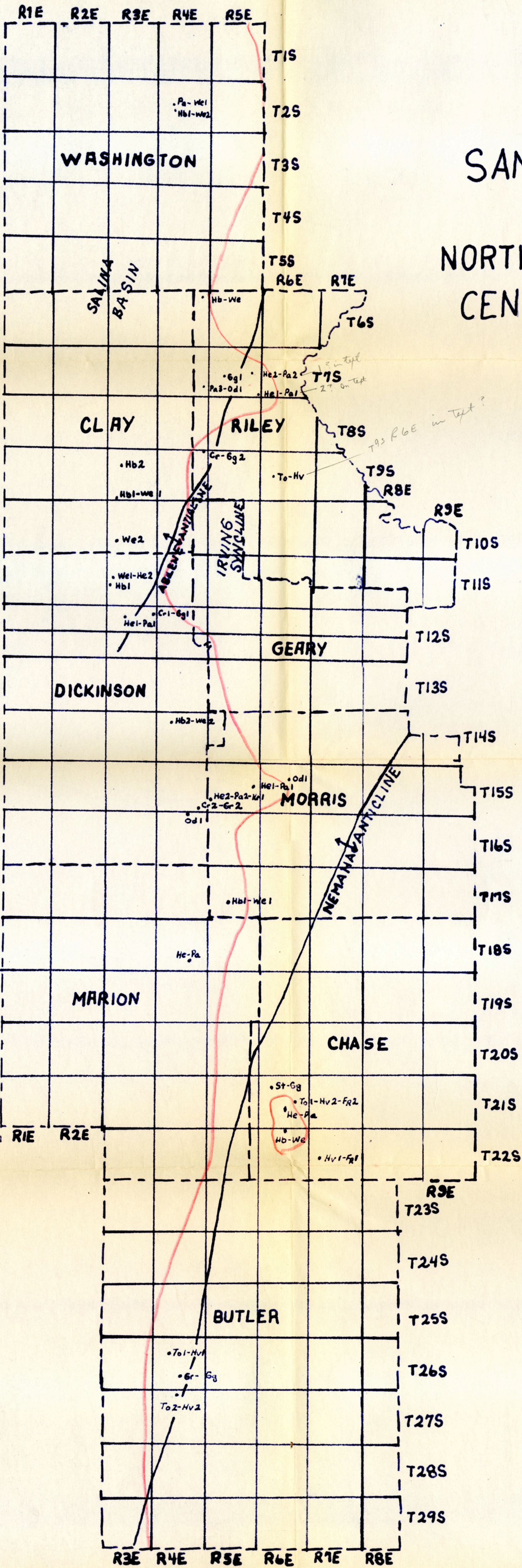   Am. Jour. Sci., vol. 257:29-43. 1959.

APPENDIX

Fig. 1   Sample index map of North and East Central
Kansas

C_{LA}HAMPION N<u>O. K-68</u>
7 X 10

SAMPLE INDEX
MAP OF
NORTH AND EAST
CENTRAL KANSAS

FIGURE 1

HERINGTON
OUTCROP

Fig. 2 Stratigraphic correlation chart

STRATIGRAPHIC CORRELATION CHART OF THE UPPER CHASE AND LOWER SUMNER GROUPS IN NORTH AND EAST CENTRAL KANSAS
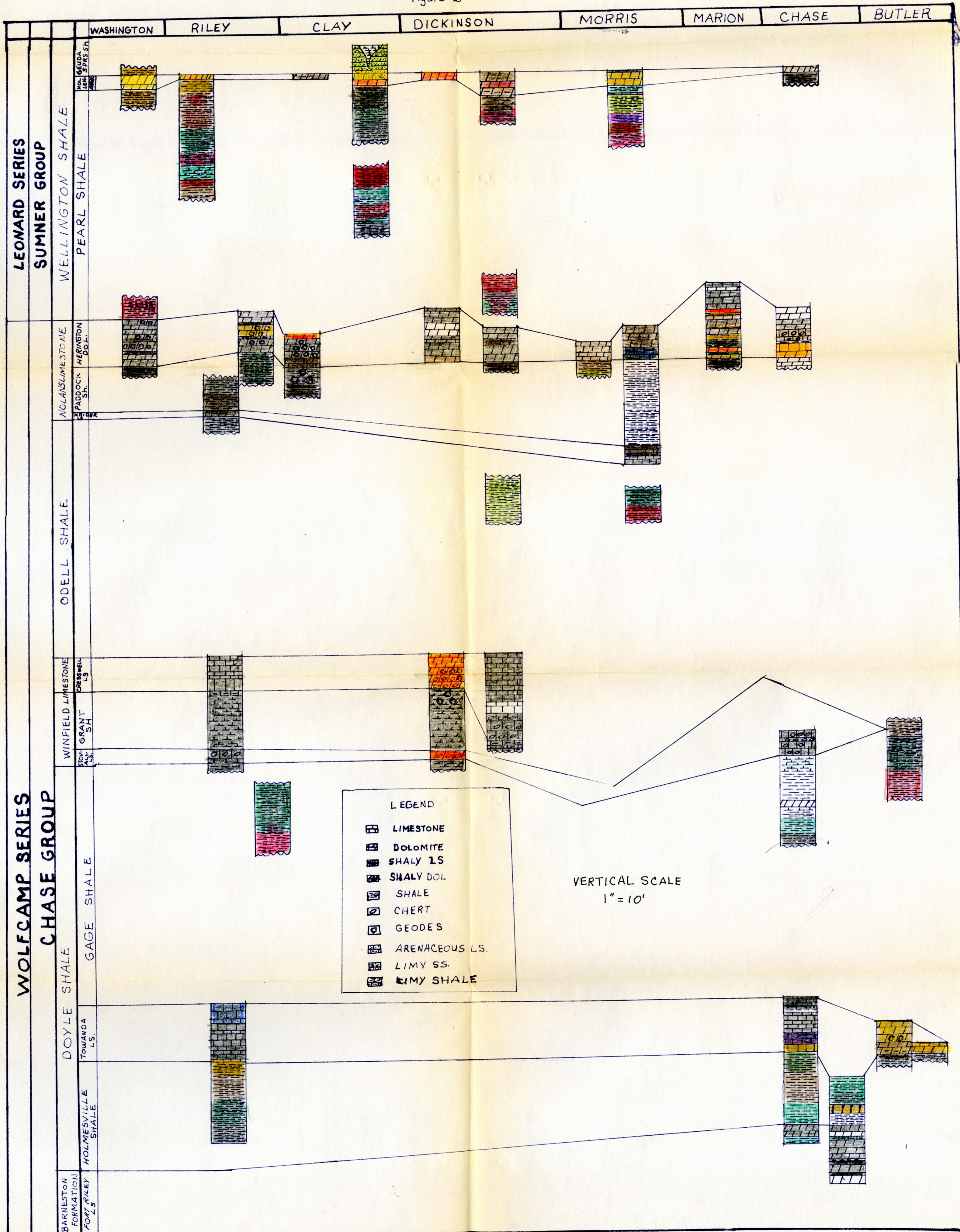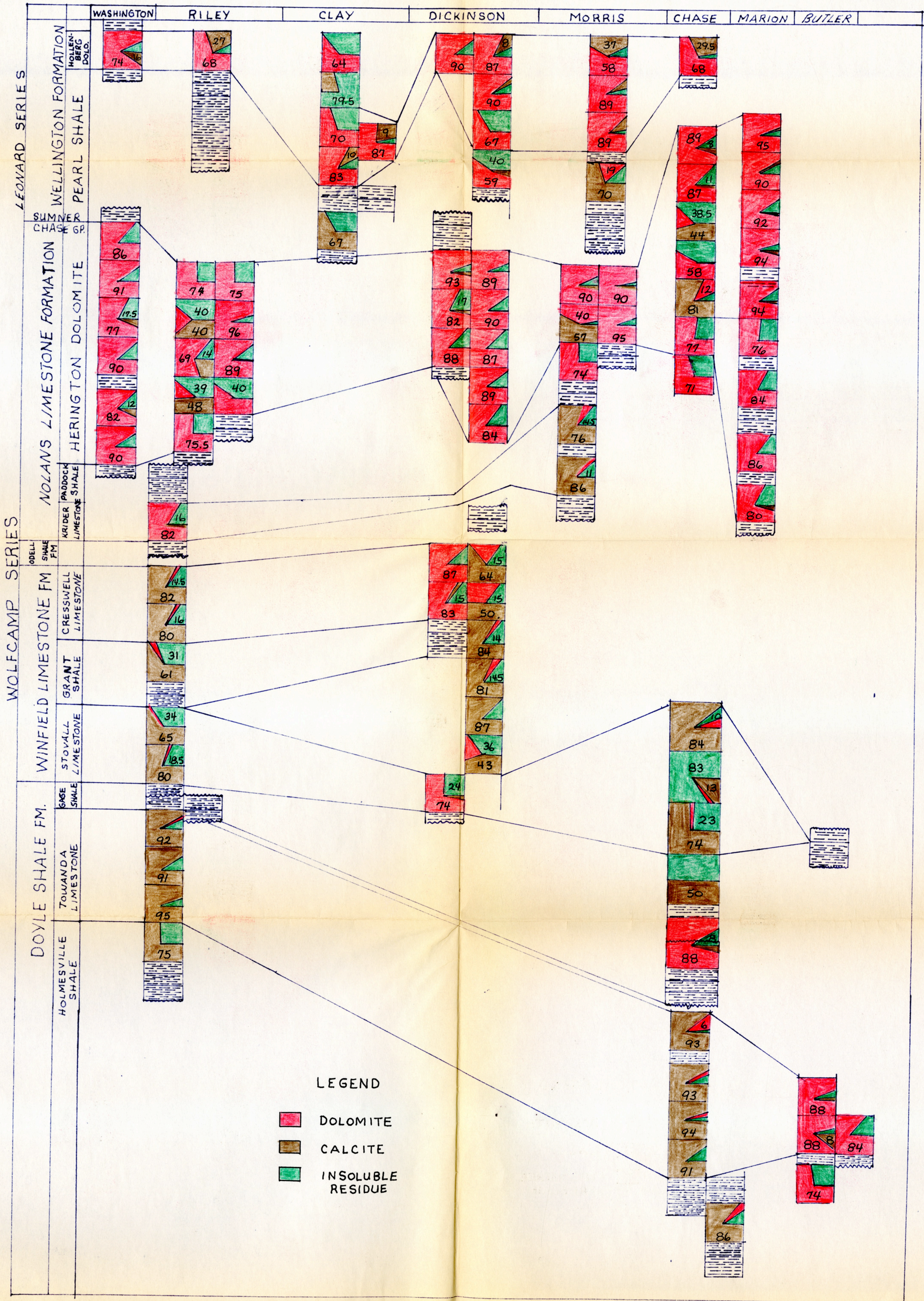
Figure 2

LEGEND

- Limestone
- Dolomite
- Shaly LS
- Shaly Dol
- Shale
- Chert
- Geodes
- Arenaceous LS.
- Limy SS.
- Limy Shale

VERTICAL SCALE
1" = 10'

Fig. 3 Carbonate-insoluble residue relationship
         diagrams

CROSS SECTION OF CARBONATE MINERAL-INSOLUBLE
RESIDUE RELATIONSHIPS IN NORTH AND EAST
CENTRAL KANSAS

FIGURE 3

CLAY MINERALOGY AND CLAY PARAGENESIS OF THE
UPPER CHASE AND LOWER SUMNER LIMESTONES
AND SHALES IN NORTH AND EAST CENTRAL KANSAS

by

WILLIAM RONALD BRYSON

B. S., Kansas State University
of Agriculture and Applied Science, 1958

AN ABSTRACT OF
A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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OF AGRICULTURE AND APPLIED SCIENCE

1959

The purpose of this investigation was to determine the clay and carbonate mineralogy of the limestones, dolomites, and shales of the Upper Chase and Lower Sumner Groups in North and East Central Kansas. Samples were taken from quarries and road-cuts and, wherever possible, paired samples of weathered and un-weathered rock were collected to afford a comparison of clay mineral assemblages.

The methods employed in this investigation included X-ray diffraction, differential thermal analysis, and ion exchange. Powder diffraction patterns were used to compare the relative amounts of quartz, dolomite, and calcite. Insoluble residue analysis was restricted to percentage determination.

From this investigation the following observations were made:

1. The clay mineral assemblages in a given area are determined partly by environmental conditions at the time of deposition and probably even more by the influence of subaerial weathering processes which have taken place since re-exposure to the surface.

2. Clay mineral trends follow the regional structures such as the Nemaha Ridge, Salina Basin, and Abilene Anticline, in that illite and chlorite are the dominating minerals in the basin, and various progressions of montmorillonite-chlorite interlayer complexes parallel the anticlinal structures.

3. The best evidence for the preservation of illite and chlorite in marine environments is that these minerals

comprise the entire assemblage in Washington County which is in the Salina Basin. The interlayers were formed in brackish water and closer to the source area.

4. The presence of dolomite apparently correlates in part with poorly crystalline chloritic clay. This condition is most apparent in the Hollenberg and Herington where the subaerial weathering has been most severe.

5. Clay mineral montmorillonite in the free state also seems to be most prevalent at the top of a given section where weathering is most severe.

6. Interlayered clays show good crystallinity in the shales and poorer crystallinity in the carbonate rocks. Montmorillonite-chlorite usually degrades to montmorillonite vermiculite in the carbonate rocks.

7. A major clay mineral break occurs at the Gage shale-Towanda contact, indicating a rather rapid change in environments from marine to brackish water conditions.

8. A siliceous carbonate rock can be told by the high amount of colloidal or clay sized silica present. Detrital constituents such as free quartz do not generally show up in this manner.