Distribution, Character and Basic Properties of Cherts in Southwestern Ontario

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A study has been made of the cherts occurring in southwestern Ontario with the purpose of establishing a classification system for use in laboratory testing programs, field performance studies, and the subsequent rating of chert for all mineral aggregate uses. Field relationships of nodular and gravel chert were investigated, and laboratory studies made of their mineralogy by petrographic, X-ray, and chemical analyses. Physical and mechanical properties of each type of chert were measured as well as the potential chemical reactivity and resistance to freeze-thaw disruption and volume change.

Cherts were divided into seven types, and it was concluded that the method of classification employed could be used, but an integrated knowledge of the character and basic properties of each variety is required to insure accurate visual identification.

A map is included which shows the approximate locations of gravel pits, the percentage of chert in certain areas of the province, and other data resulting from the study.

•THE INVESTIGATION of chert distribution, both in bedrock and gravels, and the determination of those characteristics and properties significant to the qualitative evaluation of chert, form part of a study designed to correlate the basic properties of chert in southwestern Ontario with simulated laboratory tests of durability and actual field performance. The boundaries of the area of study were chosen to include the chert-bearing bedrock formations of major importance and Pleistocene gravels with measurable quantities of chert.

It has been recongized for some time that chert occurring in Ontario can be divided into different types, but the subdivision into specific groups with similar properties has not previously been attempted. Examples of unsatisfactory performance are common throughout the study area, but it is felt that some varieties of chert may be qualitatively satisfactory. This study is in part directed towards the clarification of this belief.

Failures in asphaltic concrete appear to be due mainly to disintegration by frost action and mechanical instability resulting from poor asphalt adhesion. Figure 1 shows disintegration of a pavement surface course containing most of the recognized varieties of chert, due to little or no adhesive bond between the aggregate and the cement. The disintegration of portland cement concrete is equally noticeable, and it would appear that all varieties of chert are capable of producing surface popouts, although the frequency and severity are much less for some types than others. Severe pattern cracking occurs in some cases (Fig. 2) but alkali-aggregate reactivity has not thus far been determined as the principal cause. Thin sections indicate that alkali-silica gel occurs in minor amounts in these concretes, but surface exudations rarely show more than trace amounts of silica.

It is anticipated that this study will not only elucidate the deleterious interactions of chert, but supply information applicable to the problem of beneficiating many cherty

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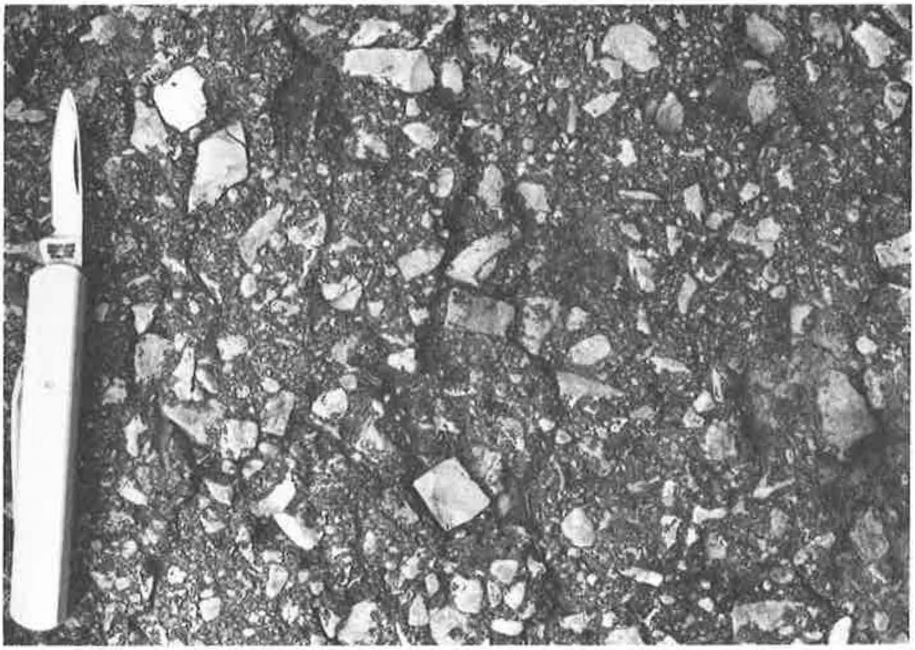

Figure 1. Asphalt disintegration due to little or no adhesion between chert particles and asphaltic cement.

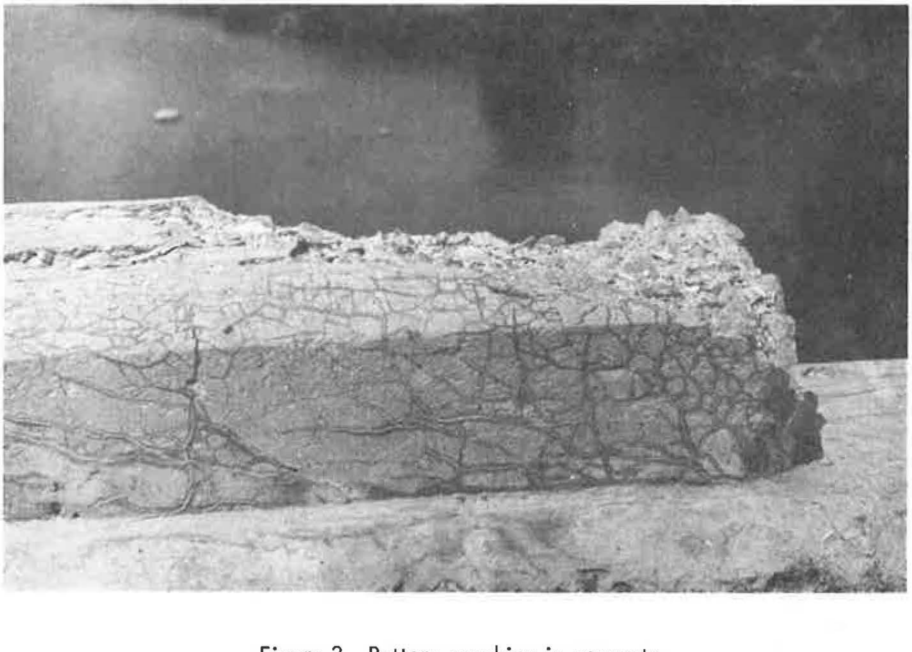

Figure 2. Pattern cracking in concrete.

deposits. The main aim is to devise a method of rating the different types of chert for use in asphaltic and portland cement concrete, based on visual classification and a minimum of laboratory tests.

OCCURRENCE OF CHERTS IN SOUTHWESTERN ONTARIO

Palaeozoic Nodular Chert

In the study area, chert occurs principally in limestones of Devonian age. Chert is present less abundantly in Silurian dolomites, and, outside the study area, in limestones of Ordovician age.

Chert is best developed in the Bois Blanc formation, which is the lowermost Devonian present throughout most of southwestern Ontario. The sequence in the study area is lithologically equivalent to the Bois Blanc formation developed in Michigan and similar to the lower Onondaga formation of New York state. The Bois Blanc outcrops along the southern border of the Niagara Peninsula and forms a narrow subsurface-band bordering Lake Erie in this region. From here the outcrop belt stretches in a broad arc across southwestern Ontario to a point on Lake Huron just south of the Bruce Peninsula. The belt averages 5 to 6 mi in width, and, although outcrops are confined primarily to the Niagara Peninsula, the cherty nature of the formation has been proved throughout the area by subsurface drilling. The thickness of the formation increases in a northwesterly direction across the area from 90 to 100 ft in the Niagara Peninsula to more than 200 ft in the vicinity of Lake Huron.

The Bois Blanc formation consists of two members: lower Springvale sandstone, which is locally developed in the Niagara Peninsula and reaches a maximum of only 11 ft, and the overlying main cherty limestone. Chert is relatively abundant in the limestone member, but occurs less frequently in the underlying sandstone except where the sandstone is represented by a sandy lower phase of the upper member.

Fifteen quarry sections and numerous small outcrops of the Bois Blanc formation were examined in detail, and bed-by-bed descriptions of the lithology were prepared. Particular attention was given to the volume and variety of chert and its textural relationship to the limestone host. Sections varied in thickness from 3 to 30 ft with the thickest exposures being in the vicinity of Hagersville. The exposures, which are all low in the Bois Blanc formation, represent only a small portion of the total thickness, but subsurface drilling and the examination of chert particles in gravels confirm the general similarity of the rest of the formation. Ten of the quarries are currently producing crushed aggregate for use as roadstone.

The lithology varies considerably both vertically and horizontally, but certain zones can be recognized and traced throughout the Niagara Peninsula area. The formation is conspicuously fossiliferous and chert-free coral biostromes and crinoid reef mounds are locally developed. These bodies grade laterally into the normal cherty limestone. Comminuted coral and crinoid debris provide most of the fossil content, but coquinoid beds rich in brachiopod and pelecypod valves also occur commonly. Relatively unfossiliferous strata, free from chert, are also a constant feature. A typical section in the Hagersville area consists of an upper fossiliferous cherty zone approximately 10 ft thick, a middle zone of approximately 10 ft of chert-free limestone, and a lower cherty zone approximately 10 ft in thickness, often more shaly with beds of argillaceous limestone. The bottom of the lower zone may be locally sandy and glauconitic.

The chert occurs in nodules of various shapes, sizes, and colors. Only the small nodules are approximately spherical, and most are more or less flattened parallel to their horizontal axes. Adjacent nodules occasionally coalesce to form lenses or beds of limited lateral extent. The thickness ranges from $^3/_8$ in. to a maximum of 9 in. with the average size being in the $1^1/_2$- to 3-in. size group. The length varies from $^3/_8$ in. to a maximum of approximately 3 ft. Lateral protuberances are relatively common but vertical projections are rare and nodules do not coalesce vertically.

Perhaps the most interesting feature of the Bois Blanc formation is the development of nodular bodies associated with the chert that are silica enriched but lack the gross characteristics of chert. These bodies are generally darker than the limestone host, but may be almost indistinguishable in hand specimen. They have been variously termed

TABLE 1

RELATIVE ABUNDANCE OF CHERT TYPES IN STRATIGRAPHIC SECTIONS EXAMINED IN DETAIL

Map Locality No.[a]	Thickness of Section (ft)	Chert Types (% by vol of total chert)									Tot. Chert Content (% by vol)
		I	Ia	II	III	IV	V	VI	VII	VIIa	
(a) Bois Blanc Formation											
1	4	4.4	—	26.0	—	—	—	69.6	—	—	35.8
2	39	2.4	—	8.6	26.7	—	—	60.6	1.7	—	62.3
3	9[b]	21.1	—	9.2	13.3	—	—	25.6	30.8	—	40.0
4	10	8.3	—	17.8	39.6	—	—	19.8	14.5	—	43.5
5	28[b]	2.0	—	28.5	34.1	6.6	0.4	17.7	7.1	3.6	—
6	5[b]	27.7	—	32.1	29.4	—	—	10.8	—	—	47.2
7	12	45.7	—	27.2	6.9	—	—	20.2	—	—	30.3
8	22[b]	23.3	—	22.1	15.3	—	—	29.9	9.4	—	45.1
9	35	11.4	—	12.5	13.7	0.8	—	36.3	25.3	—	46.4
10	31	8.4	—	23.4	23.6	0.4	—	29.6	14.6	—	40.8
11	33	—	91.2	—	4.8	—	—	4.0	—	—	24.8
(b) Delaware Formation											
12	16	—	—	9.5	75.0	15.5	—	—	—	—	8.5

[a]See Figure 3. [b]Including the Springvale sandstone member.

incipient chert (1), embryo chert nodules, and chertified limestone. The first two terms derive from the belief that the nodules are an intermediate stage in the formation of chert. However, whether or not this is the case, the latter term was preferred for the descriptive classification of chert in this study. The chertified nodules, although commonly associated with the true chert nodules, are generally somewhat smaller in size.

The volumes of chert and chertified limestone were obtained at each quarry face by direct measurement of the area exposed in the section. This was performed for each bed and each type of chert within the bed. The total volume of chert and chertified limestone calculated from these data, for each section, agreed very closely with the values determined by analysis of crushed aggregate samples. The volumes of chert are calculated for the total section, i.e., including the chert-free strata as well as the chert-bearing beds (Table 1). In the generalized section given for the Hagersville area, the upper fossiliferous cherty-beds were found to contain 6 to 33 percent nodular chert and 1 to 20 percent nodular chertified limestone. Nodular chert in the lower cherty zone constitutes 8 to 70 percent of the limestone strata and chertified nodules 3 to 26 percent. On the average, nodular chertified limestone is approximately 50 percent by volume of the nodular chert in any bed (Table 1).

Chert also occurs higher in the Devonian succession in the upper member of the Delaware formation. This section may be correlated with the Delaware formation in Ohio and the Dundee formation in Michigan. The minimum thickness has been estimated at 100 ft, and although this is somewhat less than the average thickness of the Bois Blanc formation, the Delaware dips less steeply and outcrops across a broader belt. The outcrop belt, which varies in width from 10 to 30 mi, stretches in a northwesterly direction across the central part of the study area from Lake Erie to Lake Huron. The Delaware also outcrops in the interlake peninsula east of Windsor. Since the Delaware overlaps successively lower horizons to the east and eventually rests directly on the Bois Blanc formation in the southeast part of the study area, the two outcrop belts are adjacent in the vicinity of Lake Erie, but are separated by a belt of noncherty strata along most of the outcrop band.

Chert in the Delaware formation is less commonly developed than in the Bois Blanc formation and exhibits less variety. Chert occurs in flattened nodules throughout the area, but in the south, irregular ragged nodules of white chalky chert are common, sometimes forming an anastomosing network through the limestone host. This type of chert is sufficiently distinctive that its occurrence in gravels can be readily recognized.

Two quarry sections and a number of small outcrops were examined in detail. Particular attention was given to the white chalky chert due to its abundance and distinctive character. Nodules of this type of chert were always highly irregular in shape and constituted 8 to 31 percent of the beds in which they occurred. In general, the Delaware limestone host is relatively uniform and fine grained, and does not contain any highly fossiliferous zones, such as those in the Bois Blanc formation.

The upper member of the Delaware formation is not extensively quarried in southwestern Ontario. However, its contribution to Pleistocene deposits has an important bearing on the provenance of chert in gravels throughout the study area.

In the vicinity of Hamilton, chert is present in the Middle Silurian dolomites of the Lockport formation. Although minor in occurrence, small nodules of white chert and chertified dolomite are nevertheless a distinctive feature of the Goat Island member. Chert nodules occur in this member from Hamilton to Niagara Falls, but only in the Hamilton area are they of any significance. Small chert nodules occur in the Bruce Peninsula towards the base of the Amabel formation, which is the northern equivalent of the Lockport formation. Again developed in dolomites, the cherts are similar to those at Hamilton, but less frequent.

Chert in Pleistocene Deposits

The varieties of nodular chert identified in the Bois Blanc and Delaware formations have been recognized in gravels throughout the study area. In addition, minor jasper, which is not indigenous to the area, occurs in some deposits in the northwestern section.

To facilitate the preparation of a map (Fig. 3) showing the distribution of chert in terms of the total chert content of each gravel deposit, the results of analyses from 508 deposits were plotted in the percentage ranges: 0 to 1, 1 to 3, 3 to 5, 5 to 10, 10 to 20, and over 20. Although most of the deposits contain less than 20 percent, there are localized areas with deposits containing in excess of 20 percent and some in excess of 50 percent. In all cases, the mean value was used but the range was taken into consideration in areas where the establishment of boundaries presented some difficulty. The chert fractions from 68 gravel deposits were further separated into their constituent types. Table 2 gives analyses of the chert fractions of eight deposits, traversing the study area from northeast to southwest. Analyses were made on the $^3/_4$- to $^3/_8$-in. fraction of the sample and the samples were obtained from stockpiles, open faces, and in some cases from exploratory test pits. All computed values used in the compilation of data for the map are weight percentages.

Lines of equal chert concentration could be plotted on the map, outlining zones with the ranges of chert content previously mentioned. Definite zones are defined by the boundaries which, although very irregular, approximately parallel the outcrop bands. The greatest concentration occurs along and to the southwest of the Bois Blanc and Delaware outcrop belts in two wide bands with the chert content in the range 10 to 20 percent. Areas with concentrations greater than 20 percent are much more localized and are mainly associated with the Bois Blanc outcrop. In all zones, deposits occur with significantly different concentrations of chert than the surrounding gravels; in some cases eskers had appreciably higher or lower concentrations than associated outwash deposits. However, extensive outwash trains can be traced across different zones with corresponding changes in the chert content and it would appear that minor geological discrepancies do not invalidate the belief that there is a geographical pattern for the distribution of chert. A more accurate pattern could probably be derived from the chert concentration in associated tills, but the zones established are remarkably consistent and concur with the stratigraphic occurrence of chert and the movements of glacial ice through the study area.

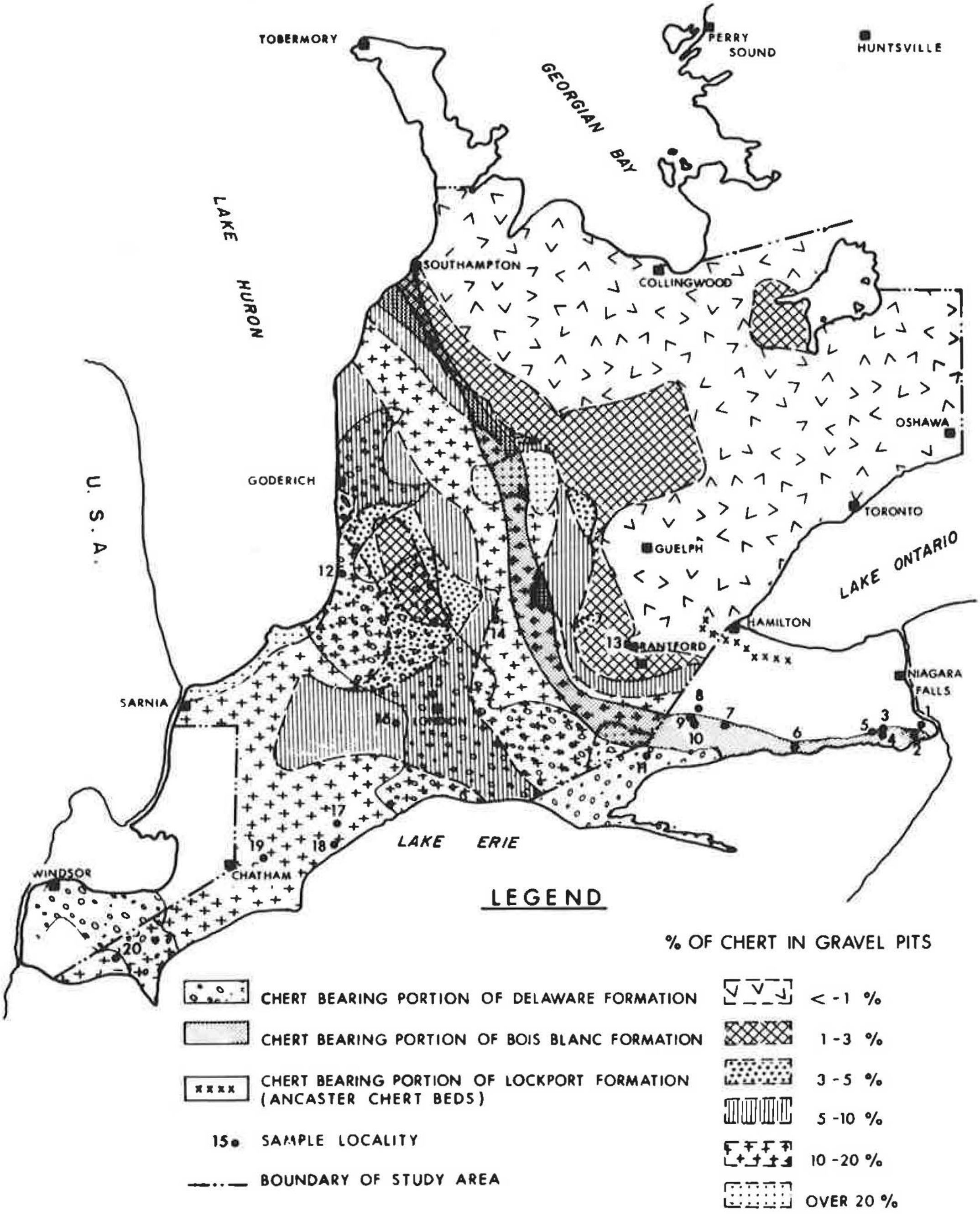

Figure 3. Distribution of chert in gravel deposits in southwestern Ontario.

The provenance of chert is complex, but in many cases it is possible to differentiate between varieties derived from the Bois Blanc formation and from the Delaware formation. Chert from the Lockport formation and Black River group occurs too infrequently to identify in gravels. Chert from both the Bois Blanc and Delaware occurs over a wide area on either side of each outcrop belt. Delaware chert occurs only rarely northeast of the Bois Blanc outcrop and increases proportionately in a southwesterly direction.

TABLE 2

RELATIVE ABUNDANCE OF CHERT TYPES IN PLEISTOCENE GRAVELS

Map Locality No.[a]	No. of Samples	Chert Types (% by wt of chert fraction)							Tot. Chert Content (% by wt)
		I	II	III	IV	V	VI	VII	
13	1	43.0	—	14.1	—	—	42.9	—	1.7
14	5	44.9	23.8	5.1	—	—	26.2	—	15.0
15	4	32.2	17.7	9.8	1.6	—	38.7	—	5.0
16	3	46.6	23.4	3.0	1.4	—	25.6	—	10.9
17	1	47.3	26.8	14.6	—	—	11.3	—	12.4
18	7	51.4	22.0	4.3	0.9	—	21.4	—	7.6
19	4	27.2	14.2	22.9	—	—	29.8	5.9	9.7
20	1	52.2	20.4	1.4	—	—	26.0	—	11.2

[a]See Figure 3.

The area between the two outcrop belts contains significant proportions of chert from both formations, with Bois Blanc chert predominating and only isolated deposits along the north border of the Delaware outcrop appear to contain equal quantities of both. Gravels in the study area west of the Delaware outcrop contain relatively more Delaware chert. There is apparently no pattern to the distribution of different types of chert except where white chalky cherts from the southern part of the Delaware outcrop are locally concentrated.

Thus the chert content of Pleistocene gravels in southwestern Ontario reflects in a general way the proximity of underlying chert-bearing formations. The variation in concentration within each deposit is also apparently influenced by the local derivation of the chert. In a number of deposits the variability of the chert fraction was examined in relation to the variability of the other components. Two deposits of outwash gravel were examined in detail. In one case, 37 samples from test pits and open faces provided a cross-section of the deposit and gave a coefficient of variation of 27.3 for the chert content and, in the other case, 17 production samples over a 2-yr period gave a coefficient of variation of 23.4. The igneous fractions had coefficients of variation of 9.1 and 9.8, respectively. The variation in these two cases is somewhat greater than the average but due cognizance was taken of this inherent variability in the establishment of boundaries on the map.

Gravel-size particles of chert show only superficial weathering, so that crushed gravel chert is essentially the same as the quarried nodular variety. Incipient alteration by weathering agents is apparent in the brown or reddish brown patina developed on those varieties of chert containing appreciable iron (i.e., types III and IV which are described in the following section of this report). Some varieties of types I and II may be outwardly buff colored from the liberation of smaller quantities of hydrated iron. Particles containing negligible iron are generally somewhat lighter in surface color than their nodular parent material, due apparently to higher porosity. This layer, however, is confined to a surface skin of insignificant thickness, and there is microscopic evidence to suggest a depletion of carbonates, possibly due to leaching. Quarry cherts subjected to unconfined freezing and thawing frequently became lighter surficially after prolonged exposure, and thus this phenomenon may in part be physical in nature.

CLASSIFICATION OF CHERTS

Originally the cherts examined were divided into a large number of groups following techniques adopted by other investigators (2, 3). For the most part, classes of chert were based on small differences in color, and it soon became apparent that this system was difficult to apply in practice. Preliminary tests further indicated that some of the groups had sufficiently similar basic properties that they could be combined to facilitate recognition for bulk separation. Textural relationships with the carbonate host rock were of fundamental importance, insofar as cherts from different locations were similar in appearance when developed in carbonates of the same texture, and played a significant part in the conceptual classification of the chert nodules. While recognizing the heterogeneity of groups based on such characteristics, it was felt that the subdivisions were more or less consistent and provided a reasonable approach to the visual segregation of chert nodules for analysis.

The collection of samples was greatly influenced by the establishment of chert types, for, whereas particular attention was paid to the collection of the most abundant nodules at each exposure, every effort was made to insure that all the varieties present were included. Bulk samples for tests requiring a large amount of material were procured wherever possible from large nodules or lenses, and orientated specimens for microscopic, chemical, and mineralogical study were obtained from nodules considered to be most typical of each variety of chert.

Type I Chert

In the upper strata of Bois Blanc exposures, zones of white, pale buff or yellowish chalky chert occur. The nodules are somewhat smaller than associated light grey cherts but frequently are a combination of both types. A zone of white chert of this type is locally developed in the lower Springvale sandstone member in the Hagersville area. The most noteworthy development of this type of chert is probably in the southern part of the Delaware outcrop, where it occurs almost to the exclusion of other varieties. Minor zones of small nodules occur in the Lockport formation and Black River group. Hand specimens are soft and fracture very irregularly to display a rough surface texture (Fig. 4). This type of chert is very porous. The Delaware variety is designated I(a) where analytical results are given separately.

Type II Chert

Light grey or occasionally white or cream colored chert occurs mainly in the abundantly fossiliferous upper strata of the Bois Blanc formation (Fig. 5). Chert of this

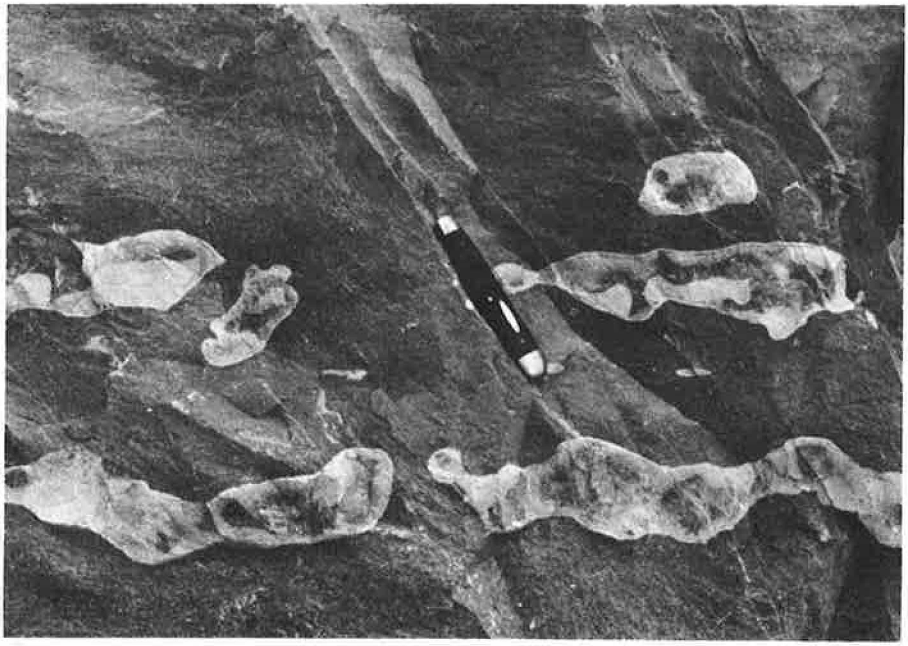

Figure 4. Irregular nodules of white chalky chert (type I) in Delaware limestone.

Figure 5. Nodule of type II chert in highly fossiliferous Bois Blanc limestone.

type occurs to a limited extent elsewhere in the Bois Blanc and in the other chert-bearing formations where fossil debris is locally concentrated, and appears to be texturally related to fossiliferous host strata. The outlines of fossil fragments are generally conspicuous and the fragments themselves are paler in color than the rest of the nodule. Hand specimens are hard and dense with a vitreous lustre and conchoidal fracture. Nodules are occasionally splintery and sometimes display what would appear to be a pseudo-cleavage, breaking into prisms along more or less vertical planes with smooth faces. White varieties of this type of chert are differentiated from type I cherts by their hardness and vitreous lustre.

Associated with chert types I and II in the fossiliferous Bois Blanc strata are small solitary corals entirely or partially replaced by chert.

Type III Chert

Medium gray, hard, dense, conchoidally-fracturing chert with a dull vitreous lustre is commonly found in fine-grained carbonates which are relatively poor in fossil debris. Occurring in all formations, it is most commonly developed in the Bois Blanc limestones and to a lesser extent in the northern outcrop of the Delaware formation. The color is somewhat variable and olive-grey, brownish-grey and greenish-grey nodules have all been described. In some nodules there are conspicuous light and dark spots or patches, giving the chert a mottled appearance. Type III chert occurs primarily in the lower zone of the cherty Bois Blanc member but is also present in the upper fossiliferous beds in relatively unfossiliferous interbedded layers. This type of chert is perhaps less splintery than type II, but a similar pseudo-cleavage is noticeable. In one or two cases, thin elongated nodules split into cubical fragments, and in other cases into thin curved plates more or less perpendicular to the bedding. Further division of these fragments may produce a conchoidal fracture or a similar smooth surface.

Type IV Chert

This group was established for cherts essentially similar to type III but dark grey in color. The remarks pertaining to type III chert apply equally to this type and in general

Figure 6. Nodules of incipient chert (type VI) in medium bedded Bois Blanc limestone.

the two groups may be considered to comprise a single unit. However, for comparative purposes, the mineralogy, chemistry, and basic properties of this type have been investigated separately to provide more data on the visual identification of chert by color.

Type V Chert

Although only of minor occurrence in the Bois Blanc formation and Black River group, this type of chert is sufficiently distinctive to merit separate classification. Black in color, it is hard and dense with a waxy lustre and conchoidal fracture. It occurs in small nodules in fine-grained limestones, frequently with thin carbonaceous shale seams. In the Black River group it occurs in a very fine-grained calcilutite.

Type VI Chert

Chertified limestone, prominent as nodular bodies in the Bois Blanc limestone, is a type readily identifiable visually (Fig. 6). The stratigraphic and textural relationships of this type have been described previously. It has an irregular to subconchoidal fracture and in general a surface texture and lustre similar to the limestone host. The lustre may, however, be porcelanous.

Irregular bodies of chertified sandstone occur in the Springvale member of the Bois Blanc but are texturally quite different from the nodular chertified limestones and are insignificantly developed.

Chertified dolomite, where developed, falls within this group.

Type VII Chert

Small to medium sized, flattened, ellipsoidal nodules of chert occur in the lower zone of the cherty Bois Blanc in beds of argillaceous limestone (Fig. 7). The nodules are bluish, greenish, or, less frequently, reddish-grey and distinguished by their porcelanous lustre and smooth fracture. They are usually discreet with smoothly curving contacts, and where developed in layers with shale seams the seams bend smoothly above or below the chert. Occasionally nodules of this type are developed in

Figure 7. Type VII nodule in argillaceous Bois Blanc limestone.

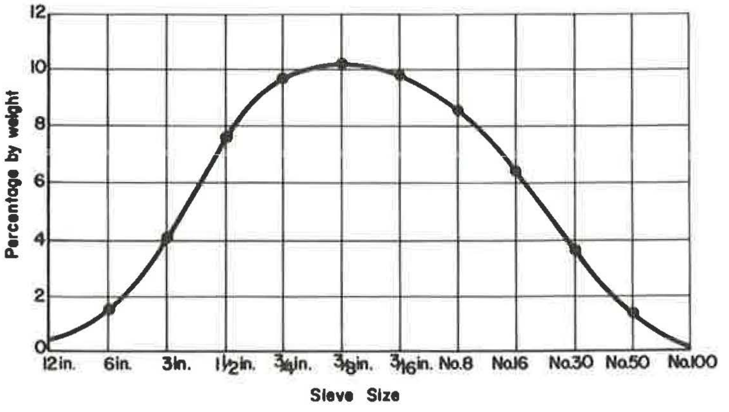

Figure 8. Size-frequency distribution of chert fraction in outwash gravel (map locality No. 16).

black carbonaceous shales at the base of the upper member of the Bois Blanc formation and then have a characteristically earthy lustre. Where analyzed separately this subvariety is designated type VII (a).

In establishing seven different types of chert, the groups are of necessity based on broad generalities, as the recognition of small differences would create an inordinately large number of categories. If the seven types described are thought of as end members, then the almost infinite variety of intermediate members poses an equally substantial problem of recognition. Fortunately, the types were more or less distinct with relatively few mixtures. In crushed aggregate, however, combinations of chert and limestone were sometimes a problem and in these cases intermediate subgroups must be used for the purposes of analysis.

Frequently, chert nodules of all types display a thin peripheral zone which is dull, porous and generally light grey in color. In one case a zone of small dark grey chert nodules was observed with very thick rim zones which coalesced laterally and vertically to form an anastomosing network throughout the bed. Isolated patches and masses continuous with the peripheral zone have been observed within the nodules, but these are generally of limited extent. The importance of the peripheral zone is that it is an integral part of the chert, mineralogically and structurally different, but, together with the chert nodule, separating from the limestone host.

Size-Frequency Distribution

Chert is not equally represented in all size fractions of the gravels. To investigate the particle size, distribution samples from several deposits were separated into their constituent size groups and the chert content determined. In general, the distribution curve was similar to that in Figure 8.

The shape of the curve would suggest a log-normal distribution resulting from some natural attribute of the parent chert-bearing formation. That the curve reflects a similar size distribution of nodular chert in both the Bois Blanc and Delaware formations is not the case here, as it would appear to be in the cretaceous flints occurring in Denmark and Britain (4). However, the size-frequency distribution of the parent chert nodules is certainly an important factor and partly controls the resulting gravel-size distribution. The nodules had a log-normal distribution with a size range from 12 to $^{1}/_{4}$ in. and a mode in the 3- to $1^{1}/_{2}$-in. size group.

Crushing curves obtained for all varieties of chert were more or less the same in each case. When bulk samples were reduced, using laboratory techniques to produce a mode in the $^{3}/_{4}$- to $^{3}/_{8}$-in. size group, the resulting size distribution was approximately log-normal but skewed in the direction of the larger sizes. Good examples of chert nodules crushed in situ have been observed with no subsequent transportation of the resulting particles. Here the distribution is again log-normal but the modal size varies slightly from one type of chert to another. The average size for type III chert is in the $1^{1}/_{2}$- to $^{3}/_{4}$-in. size group and for types I, II and VII in the $^{3}/_{4}$- to $^{3}/_{8}$-in. size group. Further, in some cases the particulate materials produced by glacial crushing are remarkably cubical in shape; this is particularly true of type III, and it has been concluded that this pattern of breaking is primarily due to the systems of microcracks in thin section. Frequently nodules of type II chert yield splintery or platy particles, presumably for the same reason, but the relative absence of flat particles in gravels indicates further breakdown by impact in transportation.

Undoubtedly, freezing and thawing were active in glacial environments, producing approximately the same results as the unconfined freeze-thaw tests which form part of this study. The general effect is to reduce the overall partical size and produce a shift in the distribution towards the finer sizes. Superimposing this effect and the crushing characteristics on the natural size-frequency distribution of the parent nodules, all of which are approximately log-normal, would result in the curve shown in Figure 8. Variations, depending on such factors as the type of chert predominating and severity of glacial crushing, do occur, and the modal size ranges between $^{3}/_{4}$ and $^{3}/_{8}$ in., but it lies typically in this size group, being closer to the lower limit with increasing abundance of type I chert.

MINERALOGY

Fifty-six orientated specimens were collected from seventeen localities and thin sections cut normal to the bedding for microscopic study. The samples included all the noticeable varieties from outcrops in the Delaware, Bois Blanc, and Lockport formations and the Black River Group. A portion of each sample was reserved for X-ray spectrographic and chemical analysis.

The essential mineral in all the cherts was quartz. The carbonate minerals calcite and dolomite were also important constituents of all the thin sections, being generally subordinate to quartz but in some sections of equal abundance.

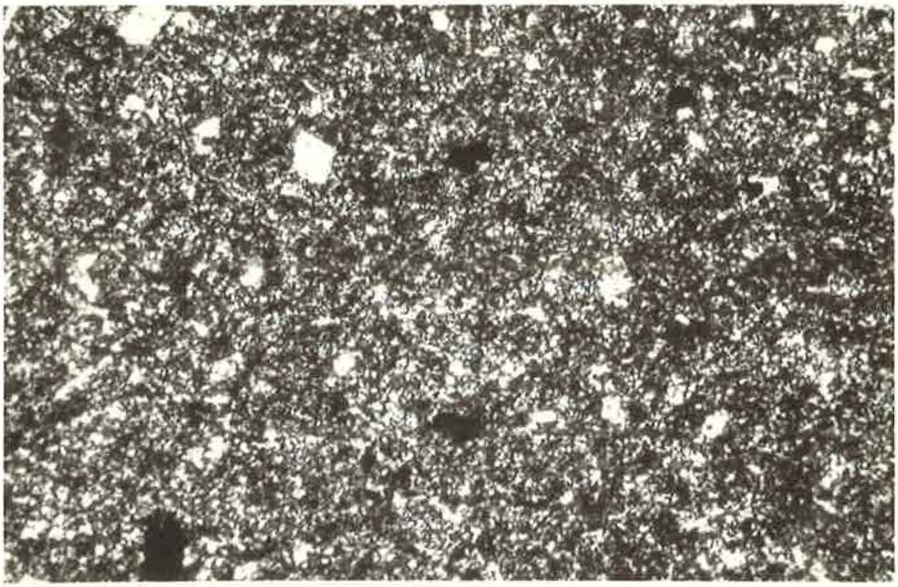

Figure 9. Typical development of microcrystalline quartz (type II chert): euhedral rhomb-shaped dolomite crystals.

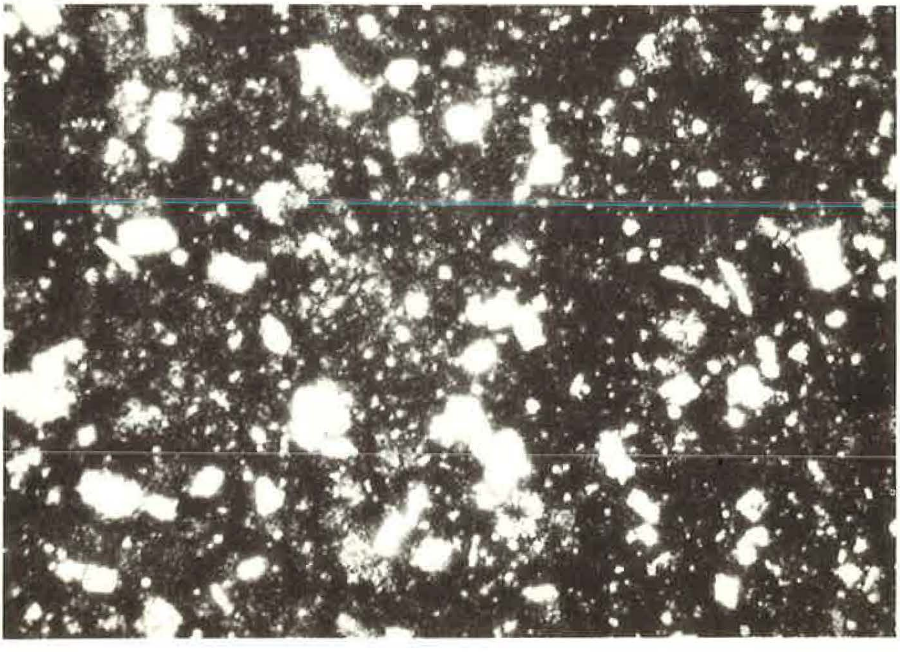

Figure 10. Cryptocrystalline quartz, approximate grain size 0.0009 mm; crossed nicols x 200.

Quartz occurs in two varieties, as equigranular mozaics and as flamboyant or spherulitic aggregates of fibres (generally termed chalcedony.) The textural terms microcrystalline (0.01 to 0.001 mm) and cryptocrystalline (< 0.001 mm) have been used for convenience in describing the granular quartz and to facilitate a comparison with other published data. These two types of quartz differ only in grain size. Quartz grains,

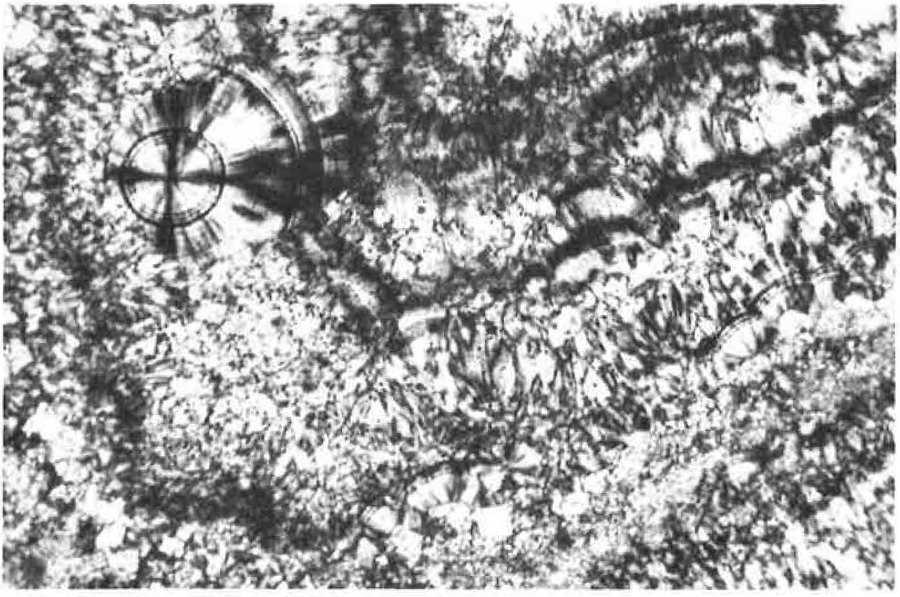

Figure 11. Typical development of plumose fibrous quartz (chalcedony) in type II cherts; the spherulitic development of fibrous quartz is shown in the upper left.

larger than 0.01 mm in grain size, do occur but are not significantly developed in most of the cherts, and where present, are confined to void or crack fillings or small isolated patches in the groundmass, with the general appearance of vein quartz.

Microcrystalline quartz (Fig. 9) is the most common variety, comprising up to 90 percent of some types of chert. The complete range of grain sizes within the textural definition were observed, but the most commonly occurring size is approximately 0.005 mm. In general, size uniformity was most noticeable where quartz had replaced an equigranular groundmass of calcite or dolomite. Microcrystalline quartz replacing large fossil fragments was frequently slightly larger in size than the average. The absence of discrete grain outlines in plane polarized light and the characteristic undulatory extinction between crossed-nicols common to microcrystalline quartz in cherts from other geographic localities (5, 6) were equally true of this type of quartz in the thin sections examined.

Cryptocrystalline quartz (Fig. 10) was present in significant amounts in only one type of chert, where its character was again similar to the same type of quartz found in geographically different cherts. The isotropic appearance of much of the groundmass shown in this figure is found in abundance only in chert type VII.

Fibrous quartz occurs as single rows of fibres lining the faces of small cracks and multiple layers of fibres in larger openings giving a banded appearance and also as small spherulites of radiating fibres. Where banded, successive fibres apparently grow from the free ends of preceding fibres and are generally longer. In one case, three successive layers of fibres, developed in a cavity, were 8, 10, and 40 microns in length. Overlapping fibres from adjacent nuclei give a plumose appearance between crossed-nicols. In plane, polarized light areas of fibrous quartz are frequently pale yellowish-brown in color, or composed of interbanded clear and colored zones. A mozaic of large quartz grains generally occupies the center of voids lined with fibrous quartz (Fig. 11).

Opal was not identified in any of the thin sections. Very minor areas of what appeared to be isotropic silica were observed in some sections, but from considerations of relief and refractive index, it was indicated that these were in all likelihood composed of ultrafine-grained cryptocrystalline quartz.

Figure 12. Microcracks in type III chert showing parallel orientation; reflected light x 150.

Both calcite and dolomite occur within the chert nodules. Dolomite is relatively common in cherts developed in limestones, but calcite was not observed in cherts from a dolomite host. Calcite is present as fossil fragments and host rock fragments, both generally deeply embayed by microcrystalline quartz, and as thin irregular veins of clear crystals. Dolomite, which is not uncommon in the limestones, is present as clear rhomb-shaped crystals in the cherts. Iron rich dolomite euhedra (ferrodolomite) or compositionally zoned crystals occur in all the cherts but most frequently in the darker varieties. Dolomite rhombs range in size from 0.01 to 0.05 mm but are most commonly 0.02 mm in diameter. In most cases, there is a concentration of dolomite euhedra at the chert limestone contact and in those cherts with well developed rim zones there is significantly more dolomite in the rim zone than in the chert or limestone host.

Accessory minerals include pyrite, glauconite, limonite, leucoxene, detrital quartz and feldspar, the latter in cherts developed in sandstones or sandy limestones. Limonite appears to be the most important; apparently admixed with some organic matter it is irregularly distributed throughout the groundmass of all types of chert, being concentrated more in the darker cherts than in the lighter varieties. It would seem that limonite and in some cases organic matter are partly responsible for the observed variation in color. Very fine mineral dust is also present in the groundmass of cherts which, from its optical properties, would appear to be a carbonate, probably dolomite.

The microscopic structure of the chert nodules tends to reflect the primary structures of the host rock, and relict shapes are common in cherts from fossiliferous or oolitic strata. However, orientated microcracks are an important original feature present in many of the cherts examined. Microcracks have been described previously in chert nodules from the Hagersville area (7), and it would appear that this is a relatively common phenomenon in nodular cherts from the Bois Blanc formation. Where developed, the cracks are approximately 0.1 to 1.0 mm in length and 0.2 to 0.5 mm apart, parallel to subparallel and at a high angle to the bedding. In reflected light, the cracks dip at more or less the same angle to the plane of section. These short cracks are somewhat different from the irregular or dendritic crack patterns developed in large areas of fibrous quartz (Fig. 12).

Type I Chert

Microcrystalline quartz is the dominant variety of quartz in this type, constituting 50 to 70 percent of the sections. It is noticeably larger in grain size than in most other varieties of chert ranging between 0.005 and 0.008 mm, with an average size of 0.007 mm. Fibrous quartz is generally not present in significant amounts but may reach 12 percent in some sections. It is developed as plumose varieties in the larger voids and as small spherulites in the groundmass.

Carbonates are important constituents of this variety of chert, in many cases comprising almost as much of the section as the quartz minerals. Calcite is a variable constituent generally in the form of ragged masses of granular limestone, showing all stages of conversion to microcrystalline quartz. In contrast, dolomite is a constant constituent, comprising approximately 20 percent of all sections as euhedral rhomb-shaped crystals.

Accessories are limited to minor limonite and mineral dust as coloring matter in the groundmass.

Type II Chert

Equigranular microcrystalline quartz, average size 0.005 mm, is the major component of the light-grey fossiliferous cherts in this group. Some fossil fragments appear to have been replaced by microcrystalline quartz of slightly larger grain size, but this is not a general condition. Fibrous quartz is a more significant component of this type than any of the other chert varieties examined. Plumose varieties of fibrous quartz are well developed in large voids created by fossil debris, in the cells of coral and bryozoa fragments and lining the inside of brachiopod and pelecypod valves, where both ventral and dorsal valves are present. Coarsely crystalline quartz is invariably developed in the centers of voids not completely filled by fibrous quartz. Spherulitic varieties are confined to minor occurrences in the groundmass and irregular cracks.

Fossil remnants are common, together with fragments of granular host rock and coarsely crystalline clear calcite cement in all stages of replacement by microcrystalline quartz. Clear dolomite euhedra are again constantly developed, but are only occasionally iron rich or compositially zoned. Less important than in type I, dolomite comprises approximately 10 percent of most sections.

Limonite and minute black rounded bodies of organic material occur sparsely and in irregular patches throughout the groundmass. Minor pyrite, occurring in small crystals, is the only other accessory of any consequence.

Microcracks are moderately common and occasionally occur in swarms 0.02 mm apart (developed in 3 out of 8 sections).

The fossiliferous limestone host in which light-grey chert is developed frequently displays small cherty spots that are peripherally milky-white with darker centers. In thin section these are voids and fossil molds with plumose fibrous quartz lining the walls of the cavity and coarsely crystalline quartz occupying the center. The matrix is comminuted fossil debris showing negligible replacement by microcrystalline quartz, even close to the chert limestone contact.

Types III and IV Chert

Microcrystalline quartz, as the major quartz mineral, constitutes 75 to 86 percent of chert types III and IV. The grain size ranges from 0.003 mm to 0.007 mm and averages 0.005 mm. Fibrous quartz is not significantly developed and, where present, occurs as small spherulites in the groundmass and short fibres lining cracks. Coarsely crystalline quartz is confined to veinlets traversing the microcrystalline quartz and passing into the host rock.

Calcite occurs as small randomly distributed fragments of granular limestone partially replaced by quartz. Dolomite euhedra are uniformly developed but proportionally the same as in the limestone host.

Limonite with minor admixed organic material is the most common accessory and is apparently responsible for most of the megascopic color variation. It is very unevenly distributed and occurs frequently in clots with finely divided mineral dust. Pyrite and leucoxene are less common but also occasionally occur in small segregations.

Microcracks are probably more often present (9 out of 18 sections) than in the variety of chert classed as type II. Generally spaced 0.1 to 0.4 mm apart, they may occur as close as 0.02 mm, in swarms. In one section, two sets of cracks almost normal to each other were observed.

Type V Chert

The black resinous or waxy cherts contain the highest percentage of microcrystalline quartz, 90 to 95 percent. The grain size varies little and is generally close to 0.005 mm. Spherulitic fibrous quartz is more important than in types II, III, and IV, and is found completely filling small spherical organic bodies, probably spores or pollen cases, as minute spots in the groundmass and filling cracks. Coarsely crystalline quartz is confined to minor irregular areas unconnected with the fibrous quartz.

Calcite is not important, and, as with other varieties of chert, is much corroded by microcrystalline quartz. Dolomite euhedra, although the same as those in most cherts, are less commonly developed.

Iron is a relatively insignificant impurity and most of the coloring matter appears to be finely divided brown organic material, irregularly distributed and frequently concentrated in areas of fibrous quartz.

Type VI Chert

In thin section, the matrix is approximately equal proportions of granular calcite and microcrystalline quartz (average grain size 0.005 mm). The microcrystalline quartz is uniformly distributed and there are apparently no areas of preferential replacement within the nodule. The chert limestone contact is relatively sharp as is the case with all of the nodular cherts. Where fossil fragments are of importance they are moderately or deeply embayed. Large unit crystals of calcite, usually pelecypod prisms, may be replaced by slightly coarser microcrystalline quartz, but frequently the replaced portions cannot be differentiated from the microcrystalline groundmass. Minute areas of cryptocrystalline quartz probably result from the replacement of segregations of shaly material and are of negligible proportions. The larger voids are lined with plumose fibrous quartz and coarsely crystalline quartz fills the central cavity. Smaller voids are completely filled by spherulitic or plumose fibrous quartz.

Dolomite euhedra are concentrated near the chert limestone contact, but within, the nodules are developed only to the same extent as in the surrounding host rock.

Pyrite, and in some cases glauconite, are minor accessories. Limonite is present as irregular patches of coloring matter, but is not common in this type of chert.

Type VII Chert

This is the only variety of chert in which cryptocrystalline quartz is significantly developed. The average grain size is slightly less than 0.001 mm with minor areas finer than this that appear isotropic between crossed-nicols. Microcrystalline quartz is relatively infrequent and occurs replacing fossil fragments. Fibrous quartz is confined to small spherulites in the groundmass and spherulitic aggregates in cracks.

Calcite is present as fossil debris in all stages of replacement by microcrystalline quartz. Euhedral dolomite rhombs are common and some of the larger grains show slight to moderate corrosion by microcrystalline quartz.

An intimate mixture of clay and organic matter occurs throughout the groundmass, giving the thin section a brownish, clouded appearance. However, the nature of the clay minerals and their textural relationship with the matrix cannot be resolved with the optical microscope. Limonite is also apparently present in the reddish or brownish nodules.

The most common accessory is silt size detrital quartz with minor feldspar. Minute grains of pyrite and glauconite are also locally common. Detrital biotite is a rare accessory.

TABLE 3

MICROSCOPIC ANALYSES

Chert Type	Constituents							
	Calcite	Dolomite	Micro-Crystal-line Quartz	Fibrous Quartz	Crypto-Crystal-line Quartz	Quartz	Acces-sories	No. of Sections
I	16.5	26.5	48.5	4.0	—	3.5	1.0	10
II	8.0	10.0	70.0	9.5	—	1.5	0.5	8
III	7.0	9.5	80.0	1.5	—	1.0	1.0	11
IV	6.5	8.0	82.5	1.0	—	0.5	1.5	7
V	1.0	1.0	88.5	5.0	—	3.0	1.5	3
VI	18.5	30.0	48.0	1.0	—	2.0	0.5	11
VII	5.0	16.0	9.0	1.0	66.0	1.5	1.5	6
VIIa	5.5	21.0	7.0	10.0	48.5	0.5	7.5[a]	2

[a]Mostly detrital quartz, some glauconite and pyrite.

Table 3 indicates the relative abundance of the major varieties of silica and carbonate minerals constituting the types of chert recognized megascopically. The results given are averages of individual measurements made on the number of thin sections indicated.

X-RAY ANALYSIS

X-ray diffraction patterns were obtained for the same powders used in the measurement of the true specific gravity. A total of 21 samples were analyzed, which included representatives of all the chert types previously described. The recorded spectra included reflections characteristic of α-quartz, calcite, and dolomite together with other minor constituents. A study of the weak reflections registered by the accessory minerals indicated the presence of trace amounts of feldspar and a mica-like mineral or minerals, and in one case chlorite. Amorphous silica is completely disordered and does not produce any recorded spectra, but opal generally consists of a cristobalite phase and an α-quartz phase in addition to the truly disordered amorphous phase (8).

TABLE 4

X-RAY SPECTROGRAPHIC ANALYSES

Chert Type	Constituent					
	Quartz	Calcite	Dolomite	Feldspar	Mica-Like Clay Minerals	Chlorite
I	41	22	37	Trace	Trace	—
Ia	52	25	23	—	—	—
II	64	11	25	Trace	—	—
III	78	14	8	Trace	—	—
IV	89	—	11	Trace	—	—
V	90	10	—	—	—	—
VI	49	26	25	Trace	Trace	—
VII	71	4	25	Trace	Trace	Trace
VIIa	45	5	50	Trace	Trace	—

No cristobalite reflections were recorded, and thus it was concluded that opal did not occur in any of the samples in measurable quantities (Table 4).

Semiquantitative determinations of the percentages of α-quartz, calcite and dolomite were made from the relative intensities of the appropriate reflections. The values given in Table 4 are calculated as percentages on the assumption that these three minerals represent 100 percent of the sample. This assumption is not strictly valid, but in most cases minor minerals constitute less than 1 percent and the discrepancy introduced by omitting them from the computation is slight. The most conspicuous feature is the presence of α-quartz as the only silica mineral and dominant constituent of each type of chert. Obviously, the varieties of quartz determined petrographically all have the same crystalline structure, that of α-quartz, regardless of form or grain size. For this reason the use of the term chalcedony to denote a distinct mineral species has been avoided here, and the designation fibrous quartz used in preference.

In general, the correspondence between petrographic and X-ray analysis, in terms of the major minerals, is good. However, in some cases there appears to have been an overestimation of the silica content at the expense of dolomite in the thin section determinations. From the greater abundance of dolomite registered by X-ray diffractometry it may be concluded that the fine mineral dust clouding these sections is for the most part dolomite in character.

Trace amounts of micaceous minerals were recorded in samples of types I, VI, and VII. Although not determined directly, glauconite is the principal mineral, and if any illitic clay minerals are present they are undoubtedly of very minor occurrence.

CHEMICAL ANALYSIS AND REACTIVITY

There are now numerous records of analyses of Paleozoic cherts in the literature, all of which emphasize the basically siliceous nature of this material. The chemistry of the cherts studied in this investigation illustrates the dominance of silica and the importance of lime and magnesia as recognized elsewhere, and also the relative unimportance of soda and potash.

Twenty-five chemical analyses were made on the same powder samples used for specific gravity and X-ray diffraction measurements, and the results given in Table 5 are averages for each type of chert. As anticipated, silica is the essential constituent and all the varieties are noticeably calcareous. In general, the silica content is in accord with the microscopic or X-ray determinations. However, the chertified limestone (type VI) appears to be more siliceous than the microscopic or X-ray results would suggest. The range, 56 to 63 percent SiO_2, is significantly different from that reported by Laird (1) of 45 to 50 percent SiO_2 for selected nodules of incipient-chert. Probably the reason for this, as mentioned previously, is the difficulty encountered in making a

TABLE 5

CHEMICAL ANALYSIS

Content	Chert Type								
	I	Ia	II	III	IV	V	VI	VII	VIIa
L.O.I.	14.35	15.0	7.97	7.33	4.10	3.90	16.75	7.20	15.50
SiO_2	65.25	64.40	79.83	81.53	85.40	89.50	59.35	75.95	60.90
Fe_2O_3	0.95	0.70	0.97	1.15	1.80	0.40	1.10	1.70	1.10
Al_2O_3	1.25	0.90	0.60	1.17	2.60	1.40	1.85	4.45	1.90
CaO	13.20	16.10	7.27	7.22	3.00	4.30	15.30	5.70	12.30
MgO	3.80	2.90	2.26	1.30	1.70	Trace	4.45	3.15	6.50
K_2O	—	—	0.23	0.39	0.82	—	0.39	1.69	1.46
Na_2O	0.03	0.03	—	—	—	—	—	0.01	—
Total	98.83	100.03	99.13	100.09	99.42	99.50	99.19	99.85	99.66

TABLE 6

POTENTIAL ALKALI-AGGREGATE REACTIVITY BY RAPID CHEMICAL TEST

Chert Type	Reduction in Alkalinity (R_c) (millimoles/litre)	Dissolved Silica (S_c) (millimoles/litre)	$\frac{S_c}{R_c}$	No. of Samples
I	160	598	3.75	4
Ia	192	530	2.76	2
II	133	583	4.39	2
III	132	555	4.21	3
IV	165	520	3.15	1
VI	159	485	3.05	3
VII	217	500	2.30	1
VIIa	185	570	3.08	1

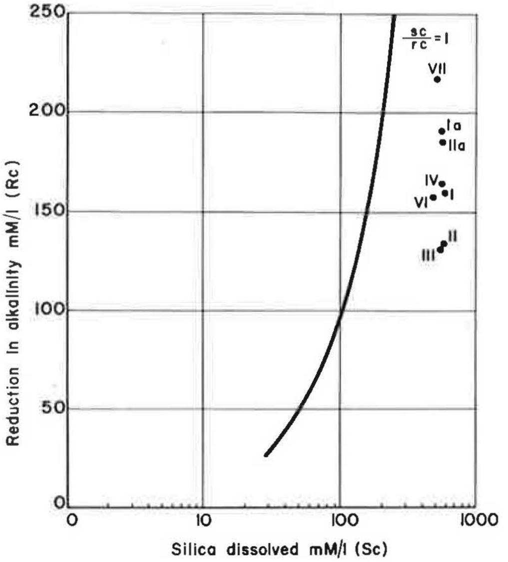

Figure 13. Potential reactivity of chert type I, II, III, IV, VI and VII by means of rapid chemical test.

suitable visual separation between particles designated as type VI and type VII in crushed aggregate.

Alumina is the most abundant minor constituent. In the chert varieties I, II, III, and IV, it is probably present in feldspar together with the potash. In type VII, the somewhat greater quantities of alumina and potash reflect the presence of glauconite as well as feldspar in the thin sections. More or less glauconite has been noted in all varieties of chert from the Bois Blanc formation, but it occurs most commonly in type VII. Iron, the remaining minor constituent of importance, is present in all the analyses and illustrates the general distribution of limonite and pyrite. Some of the analyzed iron, in type VII chert, is present in the glauconite lattice.

Chemical Reactivity

The possibility of alkali-aggregate interactions exists for all types of chert. To make a preliminary evaluation of the potential reactivity, tests were performed on 17 samples by means of the rapid chemical method (ASTM Designation C289-57T). The samples included all varieties of chert from four localities in the Bois Blanc formation, one locality in the Delaware formation, and two Pleistocene gravel deposits. Table 6 gives the amount of dissolved silica (S_c) and the concomitant reduction in alkalinity of the NaOH solution (R_c). Figure 13 shows the same results.

All of the cherts gave results indicating a high degree of chemical reactivity. The S_c/R_c ratio varied between 2.30 and 5.20 with most of the higher values registered by the more quartz-rich cherts. However, the results are variable and there is no apparent correlation between the mean value for each type of chert and either the quartz content or the porosity. It must be concluded that a complex relationship exists between both of these factors and probably between the grain-size and pore-size distribution also.

PHYSICAL PROPERTIES

Specific Gravity

The specific gravity of chert has been used as a measure of its durability and thus as a means of classifying cherts into groups of equal soundness rating. Disruption by frost action is dependent on many factors, but specific gravity is particularly useful as it is a readily determined quantity and forms the basis for certain methods of beneficiation. Specific gravity measurements were made for all the varieties of chert present in the stratigraphic sections described in detail.

Selected specimens of each variety were used to determine the bulk specific gravity and true specific gravity. The true specific gravity is essentially the specific gravity of the mineral constituents and in this study it was determined by the pycnometer method. The specimens were pulverized by grinding under water to minimize the effects of heat generated during reduction. For the purposes of comparison, selected particles of each type of chert, from a number of gravel deposits, were also used for specific gravity determinations. The gravel particles had values within the range of specific gravities for the corresponding type of nodular quarry-chert.

The appropriate mean specific gravity and range are given for each type of chert in Table 7. Differences in specific gravity exist between individual groups, although there is some overlap in certain cases. Statistical analysis indicates that at each sample locality the chert types are significantly different on the basis of specific gravity. However, examination of all the localities demonstrates that although all types are significantly different on this basis, absorption is a more reliable criterion for the differentiation of individual groups.

The true specific gravities, although consistent within each chert group, were generally lower than might be expected, and in the case of types II, III, IV and V, actually lower than the specific gravity of quartz. The phenomenon is too systematic to have occurred by chance and of sufficient magnitude to suggest a cause other than the very slight decrease in the density of quartz due to prolonged fine grinding. Possibly the failure to remove all the en-

TABLE 7

BULK DRY SPECIFIC GRAVITY OF CHERT

Chert Type	Mean	Range
I	2.175	1.841-2.368
II	2.482	2.452-2.536
III	2.582	2.541-2.598
IV	2.603	2.577-2.612
V	2.574	—[a]
VI	2.623	2.594-2.634
VII	2.446	2.409-2.488
VIIa	2.439	2.416-2.478

[a]One sample only.

TABLE 8

SPECIFIC GRAVITIES OF CHERT AND HOST ROCK

Type	Bulk Dry Sp. Gr.	Apparent Sp. Gr.	True Sp. Gr.	Theoretical Sp. Gr.
I	2.175	2.653	2.657	2.701
II	2.482	2.638	2.645	2.673
III	2.582	2.616	2.631	2.689
IV	2.603	2.626	2.638	2.686
V	2.574	2.588	2.616	2.658
VI	2.623	2.686	2.696	2.726
VII	2.446	2.668	2.670	2.712
VIIa	2.439	2.692	2.701	2.741
Bois Blanc limestone	2.655	2.721	2.731	2.730
Delaware limestone	2.645	2.725	2.735	2.733

trapped air from the mineral powder in the pycnometer determinations may partly account for the effect, as small discrepancies have been noted in density measurements of this type with very fine materials. In this case, the powders had a maximum particle size of 50 microns and mean diameter of 25 microns. It is probable that the larger particles, which are still several times the average grain size of the main quartz variety, microcrystalline quartz, contain some sealed intergranular pores, but this is unlikely in the finer sizes, raising the possibility that the minute quartz crystals contain even smaller micropores, as suggested by other investigators (6, 9, 10, 11).

To investigate the gross effects of porosity in a general way and to act as an approximate check of the true specific gravity values, a theoretical specific gravity was calculated for each type of chert from the mineralogical composition. The thin section mineralogy supported by normative mineral analyses and X-ray data was sufficiently precise to permit this. Specific gravity values for the constituent minerals were taken from the Handbook of Physical Constants, 1963 (12). Minor amounts of limonite, organic matter, and clay minerals were not allowed for in the computations, but other accessories were included where present in sufficient quantity.

The bulk-dry, apparent, true, and theoretical specific gravities for each type of chert are compared in Table 8. With the exception of the two limestones, the true specific gravities are 1 to 2 percent lower than the theoretical values for all the chert types. The theoretical calculations are of necessity approximate, but there appears to be a general relationship between the content of microcrystalline quartz and the calculated difference. So much so that at a microcrystalline quartz content of 50 percent, the discrepancy is approximately 1 percent, and at a content of 90 to 100 percent microcrystalline quartz it is approximately 2 percent. These observations are consistent with similar findings by other investigators and suggest that the differences are characteristic of quartz in this finely crystalline form.

Porosity

All varieties of chert are more or less porous, and sources of variation exist in the total pore volume and individual pore size, both within and between the chert types. Due to difficulties in measuring the size of interconnected pores, no accurate information is available concerning the size-frequency distribution of the pore systems in each variety of chert, but pertinent data on maximum pore size and the volume of pores greater than 5 microns in diameter were collected during the thin section examinations.

TABLE 9

POROSITY AND PORE SIZE OF CHERT AND HOST ROCK

Type	Tot. Porosity	Effective Porosity	Theoretical Porosity	Max. Pore Size Microns	Pores < 5 Microns (% by vol)[a]
I	18.141	18.017	19.474	50	50
II	6.163	5.914	7.146	50	80
III	1.862	1.300	3.980	10	95
IV	1.327	0.876	3.090	10	95
V	1.606	0.541	3.161	10	90
VI	2.708	2.345	3.778	50	70
VII	8.390	8.321	9.808	5	100
VIIa	9.700	9.398	11.018	5	100
Bois Blanc limestone	2.783	2.426	2.783	50	50
Delaware limestone	3.220	2.803	3.220	70	40

[a]Difference between total pore volume and estimated proportion of pores >5 microns (thin section) expressed as percentage of total porosity.

Significance has been attached to the proportion of pores smaller than 4 to 5 microns in size, and thus for the purposes of comparison with other research, the appropriate values are given in this way in Table 9.

The total pore volume, i.e., the volume of permeable and impermeable pores, was calculated for each specimen using the bulk-dry specific gravity and true specific gravity. The effective porosity (also termed apparent porosity or available porosity) being the volume of pores that can be vacuum saturated with water, was also calculated using the apparent specific gravity instead of the true specific gravity. The total porosity was calculated for comparison using the theoretical value for the true specific gravity, and is included in Table 9 as the theoretical porosity.

Total porosities as high as 22 percent were obtained for some specimens of type I chert which is by far the most porous variety. It also has the greatest proportion of larger pores, 50 to 5 microns, and, probably by virtue of this, shows the closest correspondence between the total and theoretical porosity of any of the cherts. The porosity of type VII, although less than that of type I, is still moderately high and conspicuous for the abundance of very fine pores. Type II, is moderately porous and is again characterized by a large proportion of fine pores. Types II, IV, V, and VI, have relatively low porosity but the majority of pores are relatively small. It appears that the maximum pore size in types I, II and VI is controlled by the residual limestone texture, and that in types III, IV, V and VII by the grain size of the quartz. However, the quartz crystallinity is a reflection of the original texture, and in this sense the maximum pore size in these types is also controlled by the texture of the host. The unusually coarse porosity of type I chert cannot be fully explained in terms of original texture. It has been suggested that the high porosity is due to the leaching of carbonates from nodules in strata within the zone of weathering. As this type is found far below the weathering surface, it would seem that this is not the sole cause or even the most important. In addition, nodules of this type are not enriched in silica as might be expected. The mineralogical similarity between types I and VI may have some bearing on the problem, but at this time its significance is obscure.

Absorption

The property of absorption is common to each class of chert, and the total absorption, in terms of the quantity of water absorbed in a fixed interval of time, varies considerably from type to type. In general, however, the higher the porosity the greater the absorption. Most varieties of chert exhibit noticeable suction, and again, the magnitude of this phenomenon increases with increasing porosity and absorption.

The same specimens used for the determination of bulk and apparent specific gravity were used for absorption measurements. This quantity, normally called the vacuum saturated absorption, was calculated for each type from the specific gravity experiments; the mean values are given in Table 10. In addition, the 24-hr and 1-mo absorptions were determined for each specimen by immersion in water, in an initial oven-dry condition, for the appropriate period of time. The mean values are given in Table 10. In all cases, the absorption is a percentage by volume of the bulk volume of the specimen.

Degree of saturation, which is the ratio of the amount of water absorbed in a specified time under specified conditions to the amount required to saturate the pore system of the specimen completely, has been used as a measure of physical soundness (13). In this study, the volume of water absorbed under conditions of vacuum saturation has been taken as complete saturation, and the degree of saturation at 24 hr and 1 mo is the corresponding amount of water absorbed during these periods expressed as a percentage of the former quantity. Also, the degree of saturation has been calculated as the quantity of water absorbed under vacuum saturation expressed as a percentage of the volume of water that would be theoretically required to saturate the total pore system completely. The latter value is the total porosity in Table 9. After 24-hr soaking, only chert types I, II, VII, and VII (a) have exceeded the theoretical limit of 91.7 percent for critical saturation. At 1 mo, type III has also reached this critical limit. Soaking for longer periods than 1 mo produces no change in the volume of water absorbed other than random variations that are within the limits of experimental error. The degree of

TABLE 10

ABSORPTION AND DEGREE OF SATURATION

Type	Absorption Percentage by Vol			Degree of Saturation Percentage by Vol		
	Vacuum Saturated[a]	24 Hr Soaking	1 Mo Soaking	Vacuum Saturated[b]	24 Hr Soaking[c]	1 Mo Soaking[d]
I	18.02	17.44	17.71	99.32	96.82	98.29
II	5.91	5.54	5.68	95.96	93.69	95.98
III	1.30	1.15	1.20	69.82	88.23	92.61
IV	0.88	0.72	0.77	66.01	82.32	87.38
V	0.54	0.44	0.46	33.69	80.92	84.30
VI	2.35	1.99	2.00	86.60	84.84	85.16
VII	8.32	8.20	8.24	99.18	98.68	99.01
VIIa	9.40	9.10	9.10	96.89	96.85	96.84
Bois Blanc limestone	2.43	1.87	1.97	87.17	77.23	81.01
Delaware limestone	2.80	2.22	2.39	86.96	79.19	85.35

[a]Quantity absorbed by 1 hr saturation under vacuum and 23 hr soaking.
[b]Volume of water absorbed by vacuum saturation expressed as percentage of volume required to fill total porosity.
[c]Volume of water absorbed in 24 hr as percentage of volume absorbed by vacuum saturation.
[d]Volume of water absorbed in 1 mo as percentage of volume absorbed by vacuum saturation.

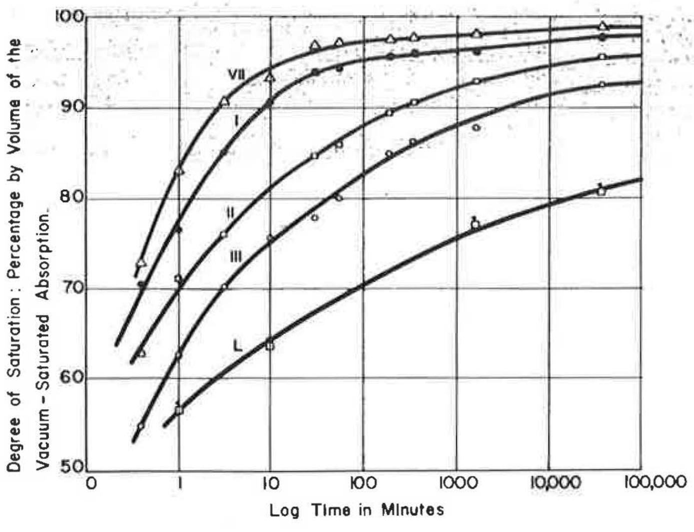

Figure 14. Rate of absorption for chert types I, II, III and VII and Bois Blanc limestone, L.

saturation in terms of the total porosity again shows types I, II, VII, and VII (a) to be critically saturated. Types III, IV and V, however, show relatively low degrees of saturation, apparently a further indication of the disparity between total calculated porosity and measured effective porosity for these varieties.

To investigate the rate of absorption, selected specimens of types I, II, III and VII were oven-dried, and then immersed in water for specific time intervals. The specimens were then removed from the water and weighed to determine the quantity of water

TABLE 11

AGGREGATE CRUSHING STRENGTH

Chert Type	I	II	III	VI	VII
Aggregate crushing value	19.0	19.5	19.5	15.0	18.8

imbibed. The results are plotted as a percentage of the quantity of water absorbed under vacuum saturation in Figure 14. Thus, in effect, any point on the curve gives the degree of saturation after a certain time interval. Although there is a great difference in the suction of different varieties of chert, the curves are more or less similar in shape. Water is imbibed rapidly for the first 10 min, and the relationship is approximately linear over this period of time. Thereafter, absorption is less rapid, decreasing to zero at 1 mo. Within 3 min, types I, II, III and VII have reached approximately 85, 76, 70 and 87 percent saturation, respectively.

Crushing Strength

Efforts to measure the compressive strength of cylindrical test specimens of chert yielded highly variable results, probably due to the heterogeneity of the specimens. To obtain some data on the mechanical strength of different types of chert, ¾- to ½-in. aggregate samples of each variety were subjected to the Aggregate Crushing Test BS, 812. No great differences are indicated between the respective losses in Table 11, although type VI has a value somewhat smaller than the rest. Perhaps of more significance is the number of cracked particles not counted as loss, which are, except for type VI, equally as abundant as the loss. In addition, types II, III and to some extent type VII, produce large numbers of flakes or splinters on fracturing which may be due, in part, to the abundance of microcracks present in many specimens of these types.

PERFORMANCE TESTS

Stripping of Asphaltic Cement

The evaluation of asphalt stripping for each variety of chert was made by means of ASTM Test, DD1664, 59T—for dry aggregates—at a water immersion temperature of 120 F for 24 hr, using 85/100 penetration grade asphaltic cement. The results given in Table 12 indicate that only type VI chert is sufficiently resistant to asphalt stripping to be suitable for asphaltic cement concrete construction.

Freeze-Thaw Resistance

The measurement of physical soundness formed an integral part of the evaluation of basic properties of different varieties of chert. Soundness is the ability to withstand disintegration or destructive volume change as a result of freezing and thawing in a wet condition. Increase in volume without particle disintegration can normally be tolerated in asphaltic concrete, but is permissible only within narrow limits in portland cement concrete. Consequently, measurements of volume change are important in the correlation of basic properties and field performance. At first the magnesium sulfate test was used to determine the disintegration, but many of the results proved to be anomalous, and the cyclical freezing and thawing of saturated unconfined particulate samples was a more suitable method.

TABLE 12

STRIPPING OF ASPHALTIC CEMENT

Chert Type	Percentage Retained Coating After Test	Remarks
I	10	Very poor
II	28	Poor
III	10	Very poor
IV	10	Very poor
VI	89	Good
VII	5	Very poor

Bulk aggregate samples of each type of chert were vacuum saturated and subjected to cyclical freezing in air and thawing in water. The duration of freezing was established at 3 hr at a cooling rate of 23 F/hr, and the period of thawing at ½ hr at a water temperature of 70 F. The testing was performed on the ¾- to ⅜-in. size group but the samples were separated into two fractions for the test, ¾ to ½ in. and

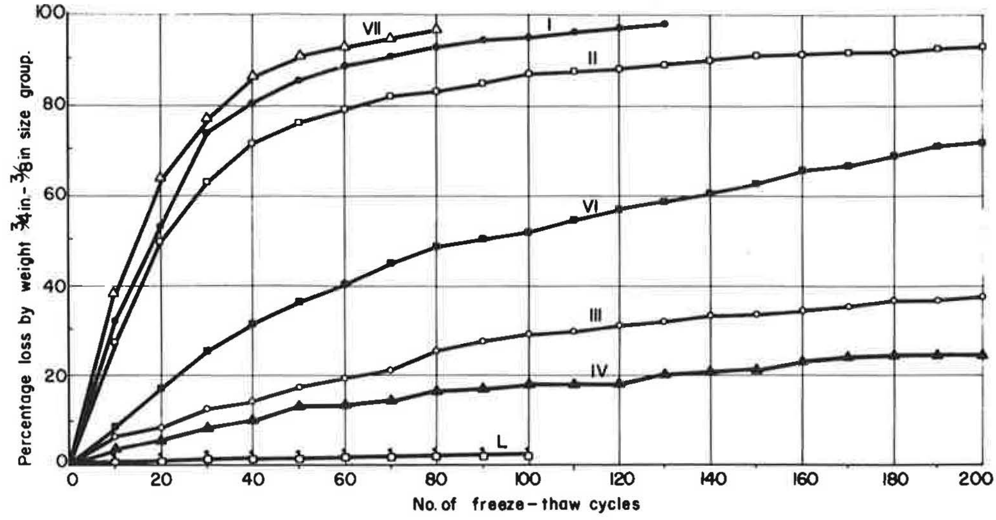

Figure 15. Disruption by unconfined freezing and thawing of chert types I, II, III, IV, VI, and VII and Bois Blanc limestone, L.

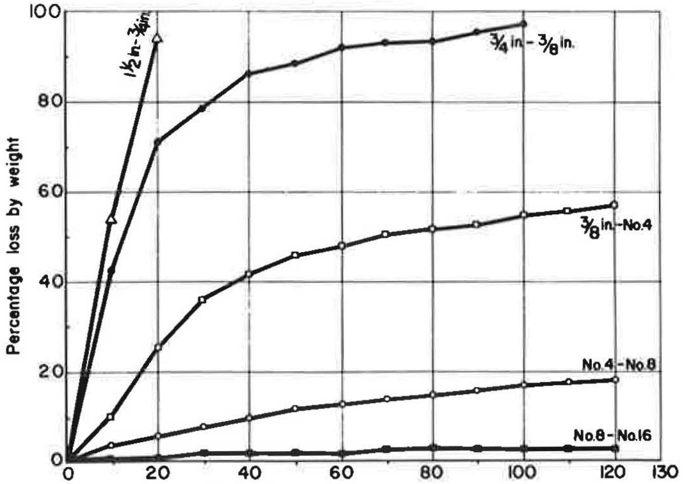

Figure 16. Disruption by unconfined freezing and thawing of individual size groups of type II chert.

½ to ⅜ in., and the results were subsequently combined. The percentage loss was determined on the finer sieve, in each case, at 10-cycle intervals. The test was carried to 300 cycles or until a loss of 95 percent was achieved. Beyond 200 cycles, however, further losses were negligibly small, and, in the case of the reference Bois Blanc limestone, no additional loss was noted past 90 cycles. The cumulative losses are plotted as freeze-thaw curves in Figure 15.

Some correlation exists between absorption and freeze-thaw loss but there is no direct relationship between the magnitude of the loss and either the porosity or the amount of absorption. A closer parallel is apparently seen between the rate of absorption and freeze-thaw losses; however, here again, although those cherts reaching the theoretical degree of critical saturation sooner have higher losses, the relative losses at a specific number of freeze-thaw cycles are not directly proportional to the rate of absorption. The specimens with high capillary suction, showing the most rapid rates of absorption and exhibiting the highest degree of water retention under vacuum drying, i.e., types I, II, and VII, form a series of closely related freeze-thaw curves of similar shape. Disintegration is very rapid for the first 30 to 40 cycles; the rate of loss then decreases abruptly and thereafter continues at a much reduced level. Types III and IV and the Bois Blanc limestone form a series of curves of somewhat different shape that show a progressively decreasing rate of loss after initial disintegration produced during the first few cycles. In view of the severity of the test, which continually exposes the particles to freezing in a critically saturated state, it is evident that a marked difference in behavior exists between those cherts represented by the two series of freeze-thaw curves. The curve representing type VI is apparently intermediate between these two types of curve. However, subsequent examination of the test samples indicated that they were a heterogeneous mixture of types VI and VII, further emphasizing the difficulty of making a precise bulk separation of these two varieties in crushed aggregate.

The shape of fragments produced by freeze-thaw disintegration is of some interest inasmuch as the microstructure of certain varieties of chert may directly influence the type of breakdown and, consequently, the recorded loss. Most of the type I particles break down immediately into small irregular fragments appearing to disintegrate by crumbling. Type II also breaks into irregular fragments, but the fragments are more angular. It is not, however, reduced immediately to fragments as small as type I, and in the majority of cases, individual particles are disrupted by only one or two fractures. Chert type VII again breaks down rapidly into smaller fragments, but in this case, predominantly thin platy fragments which may be the result of fractures along planes of structural weakness inherited from the limestone. Types III and IV, the cherts with conspicuously developed systems of microcracks, do not generally fracture through the particles, although the loss portion is composed of thin flakes, slivers, and curved plates. These minute fragments appear to originate by spalling from the surfaces of individual particles, and from the quantity it would seem that many of the particles are involved.

The concept of critical size has received much attention in literature (13, 14); it is the particulate size of a rock type of given porosity and permeability below which disruption due to freezing will not occur under a given set of conditions. To evaluate this concept in a practical way and provide data on the physical soundness of different sizes of chert, the seven size groups from $1\frac{1}{2}$ to $\frac{3}{4}$ in. through No. 30 to No. 50 were subjected to cyclical unconfined freezing and thawing using the same procedure as previously outlined. Figure 16 shows the freeze-thaw curves for each size group of crushed material from selected nodules of type II chert. The curves are all essentially the same shape but the ultimate magnitude of the loss diminishes abruptly with decreasing size. At 100 cycles the $1\frac{1}{2}$- to $\frac{3}{4}$-in. size group has registered a 100 percent loss, and the $\frac{3}{4}$- to $\frac{3}{8}$-in. group, 97 percent. The $\frac{3}{8}$ in. to No. 4, No. 4 to No. 8, and No. 8 to No. 16 groups have proportionately smaller losses which are 56, 18 and 3 percent, respectively, of the $\frac{3}{4}$- to $\frac{3}{8}$-in. loss. Sizes below No. 16 had approximately the same loss curve as the No. 8 to No. 16 size group.

Obviously, there is no critical size under the conditions of unconfined freeze-thaw testing used here, but there is a marked difference in the disintegration characteristics of different sizes. So much so that the fine aggregate fraction of a graded sample of this type of chert can be expected to show an integrated loss of only 14 percent of the coarse aggregate fraction. The freeze-thaw loss, in terms of size, is essentially the same for the other varieties of chert, modified by their relative susceptibility, as shown in Figure 15.

DISCUSSION

It is pertinent to inquire whether or not the data collected concerning the character and basic properties of the cherts are sufficiently definitive to provide a framework for classification.

In terms of the mineralogy, the content of silica, calcite and dolomite, and the variety and texture of the silica minerals, significant differences do exist. These differences apparently reflect specific textural relationships between the host limestone and the chert nodules, and support the initial subdivision into seven groups. Nodules of different types are visually recognizable by variations in color and texture. A possible exception to this generalization is type VII, which is texturally earthy to porcelanous and may be confused in bulk separation with particles of incipient chertified limestone (type VI). Field relationships are probably more diagnostic in this case. The differences between types III, IV and V may seem less significant than between the other varieties, but in view of the variation in silica content it is probably worthwhile to retain these arbitrary subdivisions until performance tests indicate otherwise.

The system of classification should provide an adequate starting point from which to assess the correlation between the basic properties and performance of chert, and subsequently a suitable scheme for the petrographic recognition and qualitative rating.

CONCLUSIONS

The occurrence of chert in southwestern Ontario has been studied both in nodular, chert-bearing limestones and Pleistocene gravels. The nodules are principally developed in the Bois Blanc and Delaware formations of Devonian age, which underlie glacial deposits in two broad arcuate outcrop belts stretching from the Niagara Peninsula to Lake Huron. In the Bois Blanc formation, chert constitutes 30.3 to 62.3 percent by volume of the limestone, and 8.5 to 24.8 percent in the Delaware formation. Particles of gravel chert derived from these two parent formations constitute from 1 to more than 50 percent of Pleistocene gravels in the area, and it was possible from the analysis of the deposits to compile a map of chert distribution showing zones of equal chert content and relating maximum concentration to the outcrop belts.

The primary purpose of the study was to establish a classification of chert, based on its fundamental character and properties, whereby different varieties can be recognized visually. Seven types of chert, numbered I to VII, were recognized on the basis of color and texture. Microscopic study revealed that microcrystalline quartz was the dominant silica mineral with cryptocrystalline quartz less common and fibrous quartz a minor constituent. Calcite and dolomite, the latter in the form of euhedral rhomb-shaped crystals, are always present and may constitute up to 50 percent of types I, VI and VII. Type VII chert is the only variety in which cryptocrystalline quartz occurs and here it is the major silica mineral. Types I to V show increasing silica content to a maximum of 95 percent. Type VI, although similar mineralogically to type I, is texturally a chertified limestone. Clay minerals are unimportant and minor pyrite, glauconite and detrital quartz are the only conspicuous accessories. Chemical analysis and X-ray diffractometry confirm the microscopic findings. Oriented microcracks were a pronounced feature in many nodules of types II and III and may be correlated with the tendency of the nodules to break into thin splinters or curved flakes.

The bulk, apparent and true specific gravities were measured for each type of chert, and the appropriate porosities calculated. An estimation of the proportion of pores smaller than 5 microns was made petrographically. Porosities ranged from 1.3 to 18.1 percent by volume and the corresponding 24-hr absorptions from 0.7 to 17.4 percent. The degree of saturation in each case was determined, and to clarify further the absorptivity, the rate of absorption was measured.

A parallel is seen between the rate of absorption and freeze-thaw soundness inasmuch as those cherts reaching critical saturation rapidly also exhibit rapid early loss in unconfined freeze-thaw tests. Although some cherts show relatively little disintegration in this test, all varieties increased in volume when subjected to frost action, approximately in relation to their porosity. This is true even for types that cannot be critically saturated.

The crushing strength and chemical reactivity were investigated, but no major differences were noted between the various types of chert. The rapid chemical test for alkali-reactivity gave results suggesting that all types are highly reactive. The content and type of silica minerals has little effect on the reactivity. Conversely, the resistance to stripping of asphaltic cement was found, in some cases, to increase with decreasing silica content.

It is concluded that different types of chert existing in southwestern Ontario can be classified visually. Color alone is not sufficiently diagnostic, and accurate classification presupposes a knowledge of the mineralogy, character, and basic properties.

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