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Glacial Marine Sedimentation and Stratigraphy of the Toby Conglomerate (Upper Proterozoic), Southeastern British Columbia, Northwestern Idaho and Northeastern Washington

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Received May 26, 1970

Revision accepted for publication March 19, 1971

The outcrop of the Toby Conglomerate extends sinuously from southeastern British Columbia to northeastern Washington. It constitutes the basal part of the Windermere System (Upper Proterozoic), unconformably overlies the beveled Upper Purcell System, and conformably underlies either volcanic rocks or clastic Windermere sedimentary rocks of the Horsethief Creek Group and Monk Formation. The Toby Conglomerate consists chiefly of diamictite, which is complexly interstratified with conglomerates, sandstones, and argillites, the latter two containing dispersed megaclasts. Toby Conglomerate thickness ranges markedly from a few to nearly 2000 m. There is a dearth of tractive-current features within Toby sedimentary rocks. The presence of overlying pillow lavas and laminated argillites, turbidites, and grain flow deposits suggest that the basal Windermere System is of subaqueous origin. Paleogeographic reconstruction indicates deposition in the sea west of the orogenic landmass, Montania, peninsular to the Canadian Shield.

Texture, composition, stratigraphic associations of Toby sedimentary rocks, and a lack of consistent regional variation suggest that the Toby Conglomerate was deposited by glacial marine sedimentation. Montania was overridden by ice traveling westward from the shield prior to Toby deposition. The basal Horsethief Creek Group and Monk Formation were produced largely by postglacial mass flow of slumped tills and deltaic deposits. This represents a new interpretation of the genesis of the Toby Conglomerate, one which accords with worldwide evidences of a Late Precambrian ice age.

Le conglomérat de Toby affleure de facor sinueuse depuis de Sud-Est de la Colombie Britannique jusqu'au Nord-Est de l'Etat de Washington. Le conglomérat constitue la base du Système de Windermere (protérozoique Supérieur) et il repose en discordance sur le Purcell Supérieur. Les roches volcaniques et détritiques du Groupe de Horse-thief et de la Formation de Monk le recouvrent en conformité. Le conglomérat de Toby est surtout formé de diamictite, interstratifié très irrégulièrement avec des conglomérats. Il contient aussi des grès et des argilites dans lesquels on observe une dispersion de mégaclasts. L'épaisseur de la formation varie de 2000 à quelques mètres. Il n'existe à peu près pas d'évidence de transport par traction dans les roches du Toby. La présence, dans les strates situées au dessus du conglomérat, de laves à coussinets, d'argilites laminées, de turbidites et de dépôts du type "grain flow" suggère que la base du Windermere fut formée sous l'eau. La paléogéographie indique que le dépôt s'est accumulé dans une mer sise à l'ouest d'une région émergée, Montania, péninsule du Bouclier canadien.

La texture, la composition et les associations stratigraphiques observées dans le Toby, ainsi que l'absence d'une variation régionale consistante laissent entendre que le conglomérat de Toby est le résultat d'une sédimentation glacio-marine. Avant la sédimentation du Toby, Montania a subi une glaciation qui se déplacit d'Est en Ouest depuis le Bouclier. La base du Groupe de Horsethief et de la Formation de Monk fut formée principalement par des glissements de till et de dépôts deltaïques.Ceci représente une nouvelle interprétation de la genèse du conglomérat de Toby, plus conforme avec les indices de glaciation continentale qui aurait eulieu à la fin du Précambrien.

Introduction

This study constitutes the first detailed description of the Toby Conglomerate of British Columbia and its stratigraphic equivalents: the Shedroof and Huckleberry Conglomerates of Idaho and Washington. These formations are exposed in a sinuous homoclinal belt of Upper Proterozoic rocks trending north–northeast for 230 km from the Huckleberry Mountains, Washington, to Bugaboo Creek, British Columbia, and in structurally dislocated patches in the north central Purcell Mountains (Fig. 1). These regions have high relief, thick vegetation, and access is difficult. Exposures may be reached by logging or mining roads and trails. Exposures are best along lake shores, in canyon bottoms, and above timber line.

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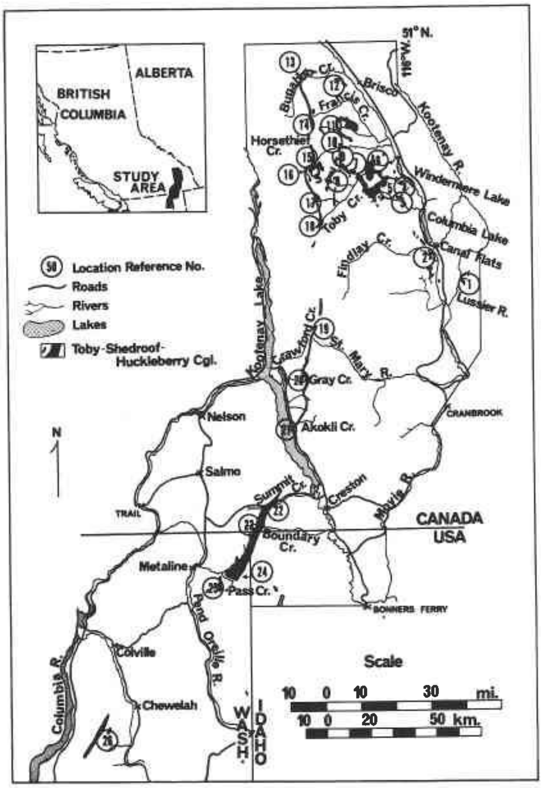

FIG. 1. Regional location map. Localities within the text and illustrations will be referred to by number or by geographic region listed below. The numerical coordinates refer to the grid system established for Canadian topographic quadrangle maps.

Canal Flats Region:
Area 1: Ram Creek, Mt. Peck Quad., 82J/3W.
Area 2: Canal Flats, Canal Flats West Quad., 82J/4W.

Central Purcell Mountains:
Area 3: Brewer Creek mouth, Fairmont Hot Springs West Quad., 82J/5W.
Area 4: Brady Creek area, Fairmont Hot Springs West Quad., 82J/5W.
Area 5: Mt. Brewer ridge, Toby Creek East Quad., 82K/8F.
Area 6: Along Toby Creek, Toby Creek East Quad., 82K/8F.
Area 7: Above Paradise Mine, Toby Creek West Quad., 82K/8W.
Area 18: Toby Creek head, Lardeau East Quad., 82K/2E.

Northern Purcell Mountains:
Area 8: Delphine Creek head, Toby Creek West Quad., 82K/8W.
Area 9: Mt. Law ridge, Radium Hot Springs West Quad., 82K/9W.
Area 10: McDonald and Horsethief Creek junction, Radium Hot Springs West Quad., 82K/9W.
Area 11: Foster Creek, Radium Hot Springs West Quad., 82K/9W.
Area 12: North of Steamboat Mt., Spillimacheen West Quad., 82K/16W.
Area 13: Along Bugaboo Creek, Bugaboo Creek East Quad., 82K/15E.
Area 14: Along Frances Creek, Howser Creek East Quad., 82K/10E.
Area 15: Horsethief and Farnham Creek junction, Howser Creek East Quad., 82K/10E.
Area 16: North of Horsethief Creek falls, Duncan Lake East Quad., 82K/7E.
Area 17: Along Jumbo Creek, Toby Creek West Quad., 82K/8W.

Western Purcell Mountains:
Area 19: Rose Pass, Kaslo East Quad., 82F/15E.
Area 20: Sphinx Mt. summit, Crawford Bay East Quad., 82F/10E.
Area 21: Columbia Point area, Boswell East and West Quads., 82F/7E and 82F/7W.

Boundary Region:
Area 22: Along Summit Creek, Creston West Quad., 82F/2W.
Area 23: Along Monk Creek, Creston West Quad., 82F/2W.
Area 24: Along Pass Creek, Metaline Quad., U.S.A.
Area 25: Along Harvey Creek, Metaline Quad., U.S.A.

Huckleberry Mountains:
Area 26: Near Stranger (Stensgar) Mt., Chewalah Quad., U.S.A.

A prominent regional structural feature, the Rocky Mountain Trench, is situated trending north–northwest along the Columbia River flowing north from Columbia Lake and the Kootenay River flowing south from Canal Flats. The distribution of the Toby Conglomerate reflects the work of Reesor (1957*a*, 1957*b*).

The Toby Conglomerate (hereafter including the Shedroof and Huckleberry Conglomerates, unless otherwise stated) is chiefly a thickly-bedded, massive, argillaceous sandstone or sandy argillite containing ill-sorted, dispersed pebble-to-boulder clasts (thus is a diamictite; Flint *et al.* 1960), which is interstratified with minor conglomerate, sandstone, and argillite. It overlies the only major unconformity in the Upper Proterozoic – Lower Paleozoic stratigraphic sequence and is conformably overlain by either volcanic greenstones or a sequence of conglomerate, sandstone, argillite, and carbonate. Its thickness is extremely variable, ranging from several to 1864 m over only a 10 km distance.

The most recent detailed mapping of each of the respective areas with exposed Toby Conglomerate was by Daly (1912), Henderson (1954), Leech (1954), Little (1950), Reesor (1957*a*), Rice (1941), and Walker (1925, 1926, 1929) in British Columbia, Kirkham and Ellis (1926) in Idaho, and Campbell and Loofbourow (1962), and Park and Cannon (1943) in Washington. The intent of these men was not to study the Toby Conglomerate in detail. However, based upon field obser-

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vations, Daly (1912, p. 142) interpreted it as a sloping seafloor deposit, Kirkham and Ellis (1926, p. 18) and Rice (1941, p. 23) as a classic basal conglomerate produced by a sea transgressing over a gently-folded terrain, and Walker (1952, p. 225A; 1926, p. 15) as a piedmont fanglomerate and/or shore zone detritus fan deposit.

The present study has led the writer to conclude that earlier interpretations of Toby genesis were incorrect. It is demonstrable that the Toby Conglomerate was deposited largely by subaqueous mudflows and submarine glacial wasting. This interpretation complements well the worldwide occurrence of a Late Precambrian ice age which has been documented by several workers (Schwarzbach 1963).

Regional Stratigraphy

The Upper Purcell System is exposed in a geanticline bounded on the west and north by the Toby Conglomerate (Table 1, Fig. 2). It consists chiefly of vari-colored argillite with lesser amounts of quartzite, detrital and stromatolitic carbonate, and volcanic rock. Primary structures and regional formation thickness and sediment coarseness variations suggest that sediment of the Upper Purcell System was derived from the Canadian Shield and deposited on a deltaic floodplain (Reesor 1957*b*, pp. 156–158).

The unconformity separating the Upper Purcell and Windermere Systems represents a period of diastrophism and erosion. Locally, it is marked by slight angular discordance, but regionally the Toby Conglomerate rests upon different stratigraphic horizons of Upper Purcell formations (Reesor 1957*b*, p. 159). The Toby Conglomerate and the conformably-overlying Irene Volcanics may be traced southwestward along strike to the Shedroof Conglomerate and Leola Volcanics of Washington. Based upon lithology and structural and stratigraphic position, these are correlative with the Huckleberry Conglomerate and Greenstone of Washington (Smith and Barnes 1966, p. 1423). Formations within the Windermere System are conformable. In areas 26 and 10, respectively (Fig. 1), Lower Cambrian quartzite and Middle Cambrian limestone rest with angular discordance upon Windermere

TABLE 1. Regional stratigraphy of the Windermere series. Formation names, approximate thicknesses in meters, contacts and correlations are based upon reports by Campbell and Loofbourow (1962), Leech (1954), Little (1950), Okulitch (1956), Park (*et al.* 1943), Reesor (1957*b*), Rice (1941), Smith and Barnes (1966), and personal field work. "C" signifies a conformable relationship between major systems. "U" signifies an unconformable relationship, whether it be an angular unconformity or disconformity

Areas (Fig. 1):	Huckleberry Mts.	Boundary Region	Western Purcell Mts.	Northern Purcell Mts.	Central Purcell Mts.	Canal Flats Region
Lower Cambrian	Addy Quartzite	Gypsy Fm. or Hamill Series	Hamill Series	Hamill Series	Jubilee Fm. (Middle Cambrian) or Hamill Series	Cranbrook and/or Eager Fm.
	– U –	– C –	– C –	– U –	– U –	– U –
Windermere System (U. Proterozoic)		Monk Fm. or Horsethief Creek Grp. (100–1500 m)	Horsethief Creek Grp. (1500 m)	Horsethief Creek Grp. (1500 m)	Horsethief Creek Grp. (1500 m)	Horsethief Creek Grp. (0–1200 m)
	Huckleberry Greenstone (920 m)	Leola or Irene Volcanics (1400–2800 m)				
	Huckleberry Cgl. (155–900 m)	Shedroof or Toby Cgl. (5–1864 m)	Toby Cgl. (120–900 m)	Toby Cgl. (57–570 m)	Toby Cgl. (15–950 m)	Toby Cgl. (13–300 m)
	– U –	– U –	– U –	– U –	– U –	– U –
Upper Purcell System (U. Proterozoic)	Deer Trail Grp.	Priest River Grp. or Mt. Nelson Fm. Dutch Creek Fm.	Mt. Nelson Fm. Dutch Creek Fm.	Mt. Nelson Fm. Dutch Creek Fm.	Mt. Nelson Fm. Dutch Creek Fm.	Mt. Nelson Fm. Dutch Creek Fm.

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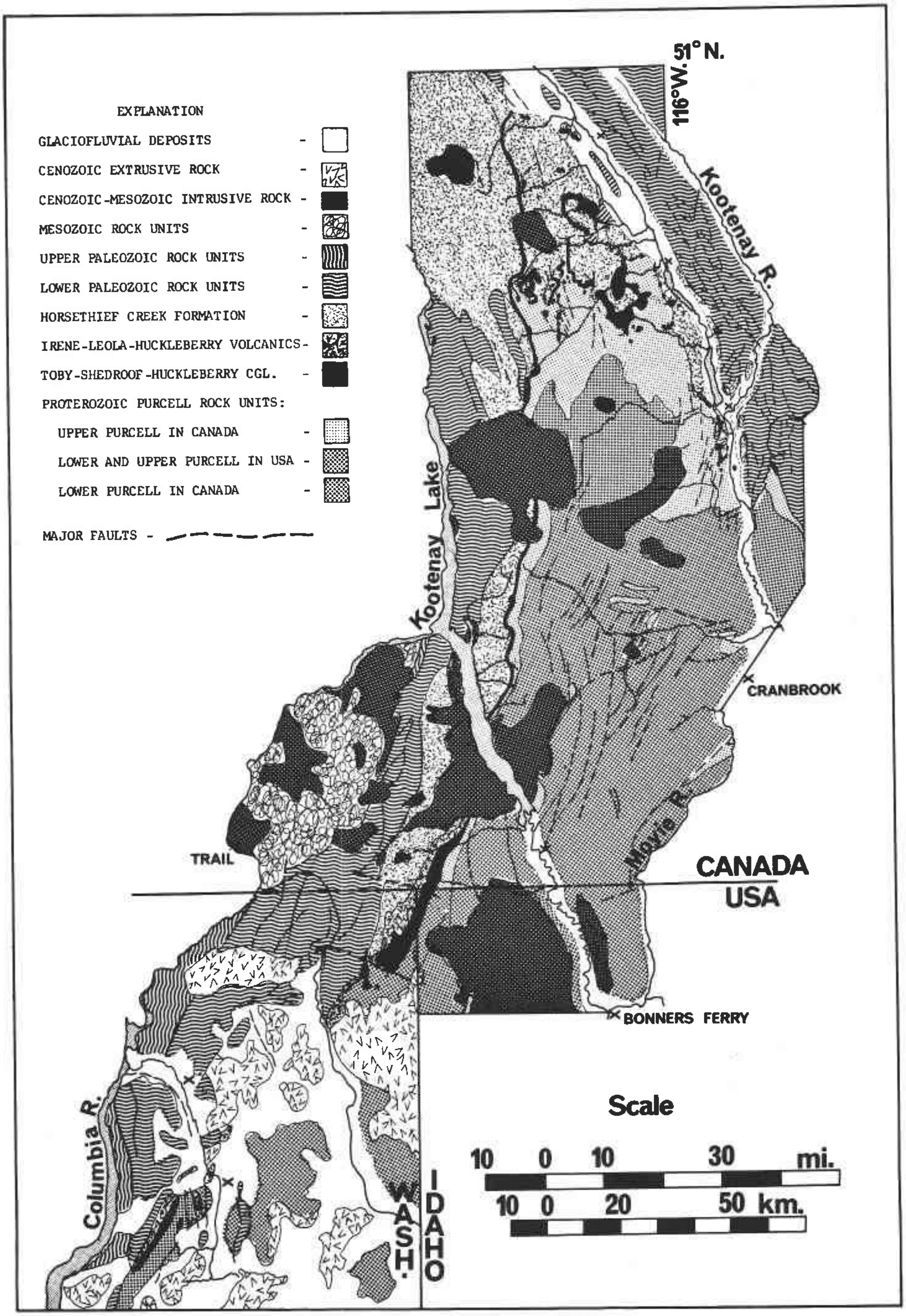

FIG. 2. Generalized regional geology of parts of northeastern Washington, northwestern Idaho, and southeastern British Columbia. The Horsethief Creek "Formation" has recently been designated a group. The figures which follow, however, were drafted before the author knew of this change and thus "Formation" appears.

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greenstone and argillite. Elsewhere, this boundary is marked by quartzites disconformably overlying beveled Windermere sediments and uncommonly by the appearance of Lower Cambrian fauna (Leech 1962*a*, p. 6; Okulitch 1956, p. 719).

Regional Tectonic Setting

The earliest structural development evident in the Purcell Mountains occurred during the East Kootenay orogeny of post-Upper Purcell and pre-Windermere age (700–800 m.y. B.P.). This involved plutonic intrusion, volcanism, broad open folding, and uplift producing a landmass in the Purcell Mountain region (Leech 1962*b*; Reesor 1957*b*, p. 170). This development was thought to have been epirogenic, but recent discovery of stocks intersecting pre-Windermere trends (Leech 1962*a*) and the presence of metamorphosed Upper Purcell clasts in unmetamorphosed Toby Conglomerate suggests that this tectonism may have been more severe. Continuing intra-Windermere epeirogeny is reflected by the presence of volcanic greenstones in the Boundary Region and Huckleberry Mountains, the beveling of parts of the Windermere System in several regions, and the variations in thickness of the Toby Conglomerate. Maturity of Lower Cambrian clastic sediments and dominance of carbonate rocks by Middle Cambrian time suggest that tectonism had waned by the end of the Precambrian.

Post-Precambrian structural overprinting has largely masked the effects of earlier orogenies in the Purcell Mountains (Figs. 2, 3; Crosby 1968). Tectonite fabrics, characterized by flow and fracture cleavage, reorientation and deformation of clasts, boudinage, and the development of small-scale corrugations in schist are typical among Windermere rocks that have been metamorphosed up to the greenschist facies (Figs. 4, 5, 14). However, primary structures within quartzites of the Upper Purcell and Windermere Systems are well preserved.

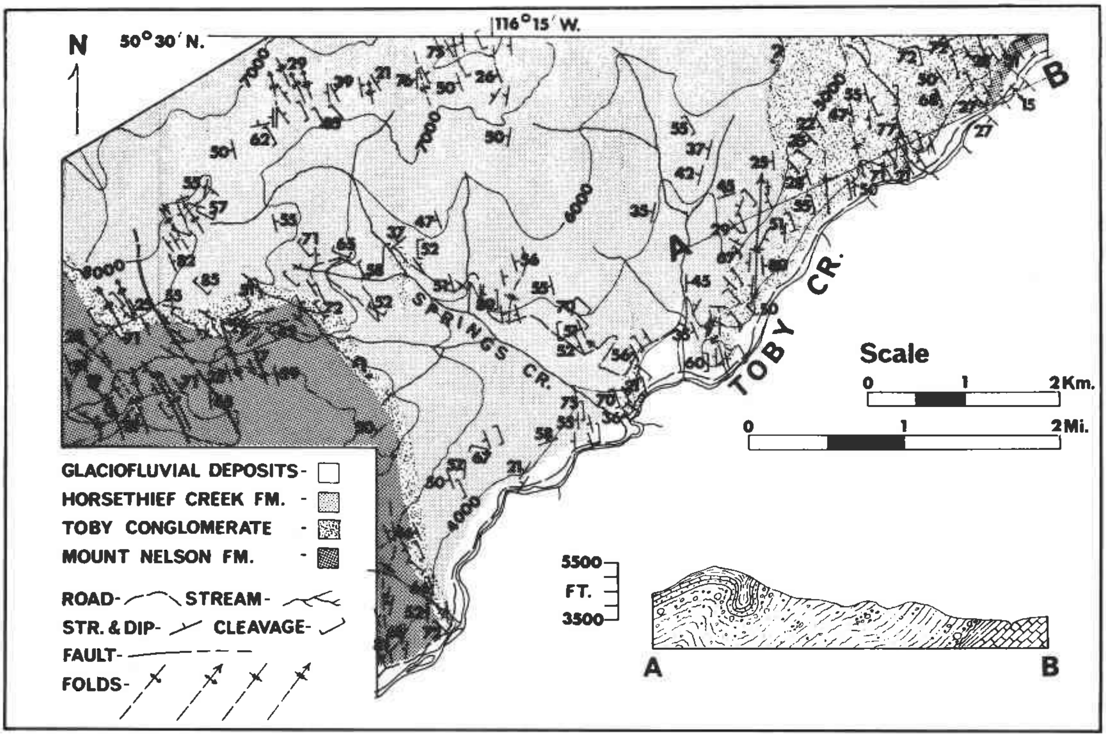

FIG. 3. Toby Creek map area. A geologic map and generalized structural cross section of the type area of the Toby Conglomerate, areas 6 and 7. Note the stratigraphic relationships of the formations present and the inferred structural complexities.

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FIG. 4. Argillaceous diamictite, Toby Conglomerate. Note the evident foliation and absence of lamination and the slight orientation of clasts parallel to foliation. Area 19, 0.6 km southwest of Rose Pass along logging road.

FIG. 5. Sandy diamictite, Toby Conglomerate. Note the evident foliation and absence of lamination, the opening of "eyes" in the ends of clasts and the orientation and elongation of clasts parallel to foliation. Area 22, 500 m west of Placer Creek along Highway 3.

The Toby Conglomerate

Introduction

The Toby Conglomerate consists chiefly of thickly-bedded or lenticular masses of diamictite, with lesser amounts of intercalated conglomerate, sandstone, and argillite. It unconformably overlies the beveled metasedimentary rocks of the Upper Purcell System and conformably underlies either Windermere volcanic or clastic sedimentary rocks.

Diamictite–Fabric

Where unweathered and relatively unmetamorphosed, the diamictite is gray, unlaminated sandy mudstone or muddy fine sandstone containing dispersed pebbles to boulders. Stratification is generally lacking. Metamorphism and deformation impart a strong foliation, a greater resistance, and green-to-silvery appearance to diamictite matrix. Extensive weathering transforms diamictite matrix to a friable, brown mass containing projecting clasts.

The pebble-to-boulder clasts supported in the matrix constitute less than 5% to as much as 65% of the rock mass, with an average of 18%. Sorting is invariably poor, with small pebbles and boulders juxtaposed and distributed randomly throughout each bed. Where clast shape has not been tectonically altered, clasts are angular-to-well rounded, the larger being better rounded (Fig. 4). Comparisons with the Powers roundness scale at 258 localities yielded a mean of 3.3 or subrounded for pebble-to-boulder-sized quartzite clasts (the least likely to be affected by

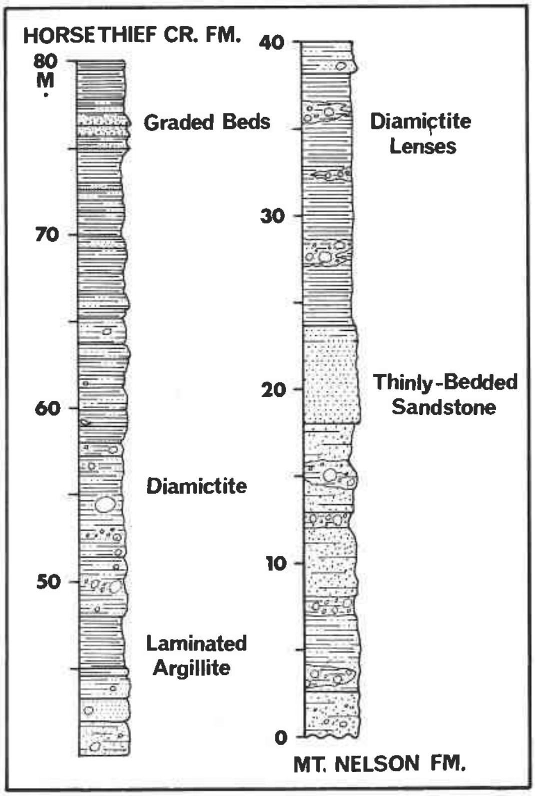

FIG. 6. Mt. Law section, Toby Conglomerate. A detailed stratigraphic section measured at the head of a cirque along the southeast ridge of Mt. Law, area 9. The contact with the Horsethief Creek Group is quite arbitrary, and could have been placed above the last diamictite bed at the 65 m level. For clarity, individual beds within a sequence of thinly-bedded graded units have been combined as several thicker beds.

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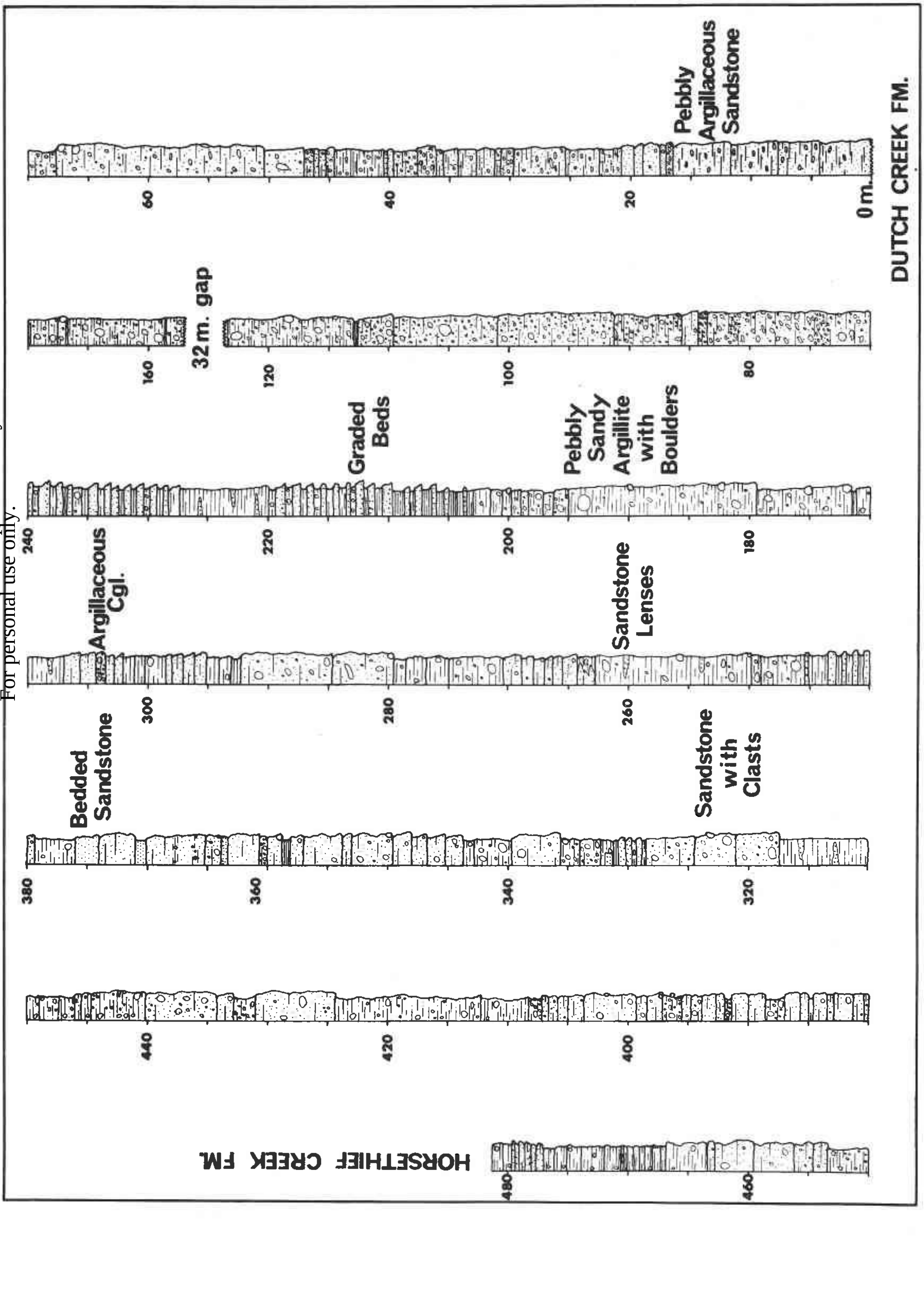

FIG. 7. Columbia Point section, Toby Conglomerate. A detailed stratigraphic section measured along the south shore of Columbia Point, area 21. For clarity, individual beds within sequences of thinly-bedded graded units or alternating sandstones and argillites have been combined as several thicker beds.

tectonic shape alteration, therefore best reflecting original roundness). Clasts are as large as 1.8 m in diameter. Average clast size distribution in diamictite beds for all regions is 76% pebbles, 17% very large pebbles, 5% cobbles, and 2% boulders.

Diamictite is contained in massive featureless lenses, commonly less than 1 m thick and 10 m long, or beds, commonly 0.5 to 5 (but up to 16) m thick, with even to gently undulating well defined contacts where cleavage is not extensively developed. Lenses are found within beds of argillite (Figs. 6, 8). Beds are interstratified with all other Toby lithologies, and are generally not laterally persistent for more than 100 m (Figs. 7, 8). Beds and lenses lack ordered internal primary fabric. In unfoliated diamictite, clasts have no primary orientation and are distributed randomly with respect to their size, position in bed, or the thickness of particular beds. Their concentration may vary laterally or vertically over a few meters by as much as 30%. Rare thin lenses of fine sandstone, generally less than 25 cm thick and 1 m long, are positioned randomly within diamictite

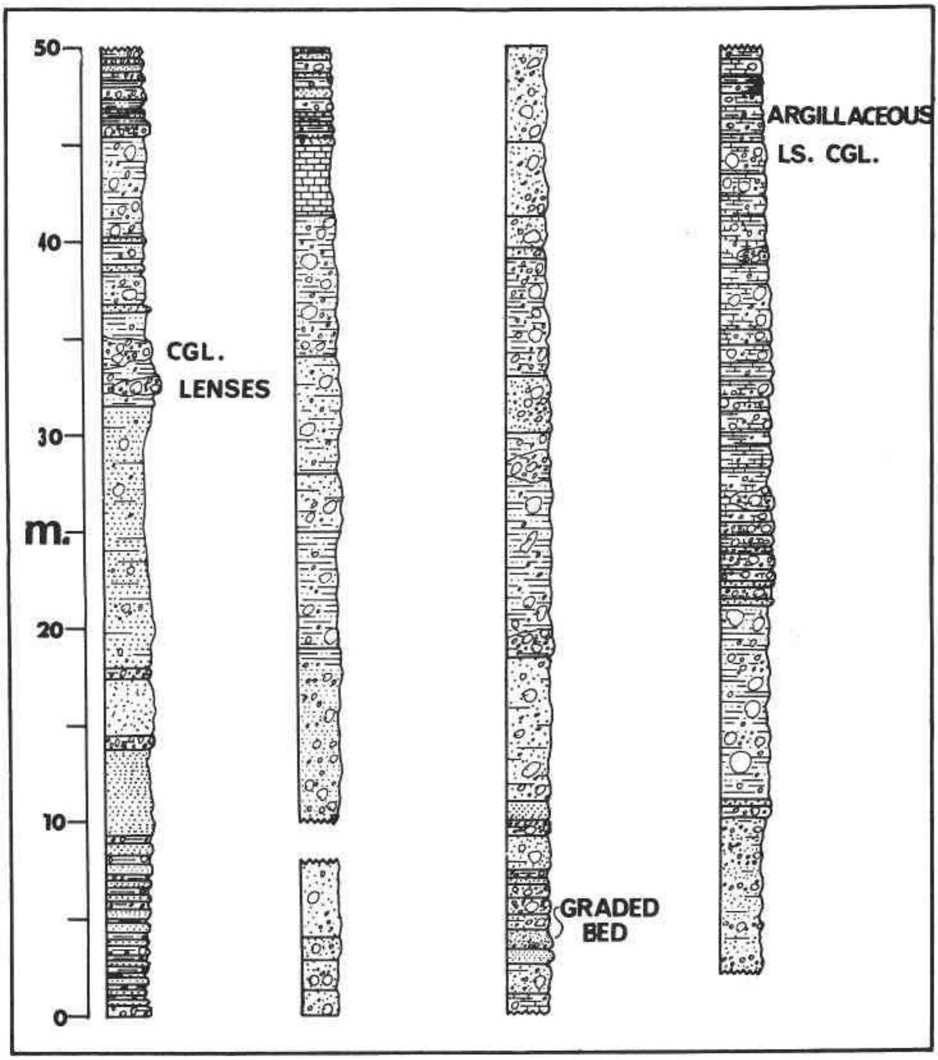

FIG. 8. Summit Creek section, Toby Conglomerate. A detailed stratigraphic section measured within basal Toby Conglomerate along Highway 3 following Summit Creek, 300 m west of Placer Creek. For clarity, individual beds within sequences of thinly-bedded alternating sandstones and diamictites have been combined as several thicker beds.

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beds (Fig. 7). Toby diamictite is distinctive in its absolute lack of megascopic or microscopic lamination, contorted stratification, and clast orientation.

Diamictite–Composition

For all regions, Toby diamictite clasts consist of an average of 61% quartzite, 26% carbonate, 11% argillite – slate – phyllite, 1% sandstone and traces (less than 1%) of conglomerate, chert, vein quartz, and plutonic, gneissic, and volcanic rock (Fig. 9). Maximum observed approximate diameters for quartzite, carbonate, and plutonic clasts are 170, 120, and 60 cm with all other lithologies rarely attaining boulder size. In most exposures, quartzite and carbonate clasts have a similar size distribution and constitute the coarsest fraction.

Quartzite clasts are equant-to-prolate, varicolored (gray, white, red, pink, purple, or tan), laminated or massive and exhibit no predepositional weathered surfaces. They were thoroughly recrystallized from fine-to-coarse quartz wackes and arenites prior to deposition, as judged from the nature of such clasts in unmetamorphosed diamictite. Detrital constituents within quartzite clasts include sericitized mudstone, recrystallized dolomite, undulose quartz with overgrowths, polycrystalline quartz, chert, albite, oligoclase, untwinned potassic feldspar, microcline, epidote, grossularite, zircon, rutile, zoisite, clinozoisite, muscovite, and quartz silt or sericite matrix in the abundances shown in Table 2. The texture is commonly granoblastic. Uncommonly, grains are stretched with crenulated borders and aligned inclusions. A high degree of premetamorphic roundness is evidenced by clear delineation of grain-overgrowth boundaries and by the presence of well-rounded heavy mineral grains. Sorting was good but is obscured by recrystallization and marginal alteration of less stable minerals. Authigenic constituents, both inter- and intragranular, include quartz, sericite, muscovite, dolomite, magnetite, hematite, goethite, and leucoxene.

Carbonate clasts are prolate-to-tabular, varicolored (gray, white, brown, red, tan, orange, or yellow, depending upon degree of weathering), and laminated or massive. They are commonly strongly recrystallized or dolomitized micritic to calcarenitic limestone. Scarce clasts include dolomitized stromatolitic carbonate, pisolitic carbonate, or micrite containing oölites or pisolites. Small amounts of polycrystalline quartz and authigenic chert or veins of dolomite may be present. Clasts are more dolomitized than calcareous matrix material, suggesting that they underwent predepositional or selective dolomitization. The clast surfaces are either unweathered or show pitting or selective solution of laminae, which may have been predepositional or produced by pressure solution during metamorphism of the Toby Conglomerate (Ramsey 1967, p. 221).

Fragments of gray-to-black laminated slate, gray-to-olive laminated slate, gray-to-olive laminated or unlaminated argillite, and green phyllite of tabular-to-bladed shapes are difficult to distinguish from diamictite matrix where foliation is pronounced. Tabular-to-prolate, gray or brown, massive sandstone and pebble conglomerate clasts show pronounced weathering. They contain grains of quartzite, acidic plutonic rock, mudstone, recrystallized carbonate or micrite, undulose and polycrystalline quartz, chert, oligoclase, andesine, untwinned potassic feldspar, and accessory and authigenic minerals similar to those of quartzite clasts (Table 2). Matrix material is quartz silt or sericite. Recrystallization, alteration, and grain overgrowth have somewhat obscured detrital texture. Most grains originally were subangular-to-subrounded and moderately sorted.

Prolate to equant, white or black chert and white vein quartz clasts are unweathered. Weathered volcanic clasts contain shard structures, chlorite pseudomorphs after pyroxene, and laths of intermediate calcic plagioclase. Even in fresh exposures, prolate granite and granite gneiss clasts have badly weathered outer surfaces. Granitic clasts contain quartz, albite-oligoclase (An 9–10), a trace of potassium feldspar, muscovite, and authigenic pseudomorphic chlorite and calcite, magnetite, hematite, goethite, and leucoxene. Some clasts exhibit micropegmatitic texture. Granite gneiss clasts contain quartz, albite, pseudomorphic chlorite, and similar opaque minerals.

Macroscopic diamictite matrix, which has not undergone extensive metamorphism, contains varying proportions of dispersed fine sand to grit. This in turn suspended in a microscopic matrix of quartz silt, clay, micrite, recrystallized dolomitized carbonate, or a combination of these (Fig. 10). The sand and grit consists of quartzite, granitic rock, sandstone, mudstone, dolomite, undulose quartz, polycrystalline quartz, chert,

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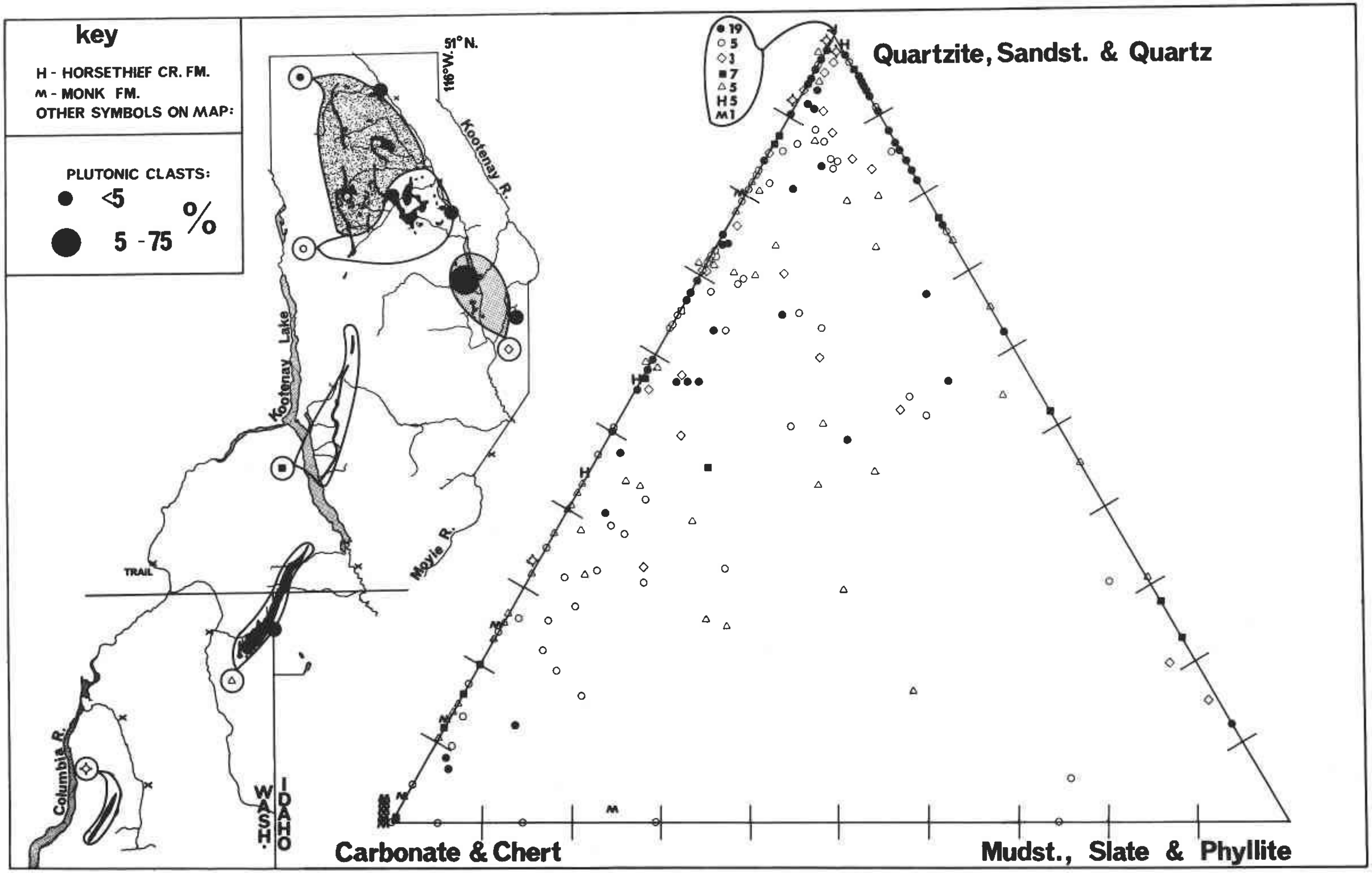

FIG. 9. Clast composition and regional variation. Conglomerate and diamictite clast compositions are given for the regions indicated by symbols on the map. These may be separated into the Canal Flats Region, the Central Purcell Mountains, the Northern Purcell Mountains, the Western Purcell Mountains, the Boundary Region, and the Huckleberry Mountains in accordance with Fig. 1. The distribution of plutonic and gneissic clasts is shown on the map. Data was derived from 260 pebble counts (including 217 of Toby diamictite, 25 of Toby conglomerate, 8 of Horsethief Creek pebble conglomerate and 10 of Monk and Horsethief Creek diamictite), with an average of 100 clasts per count.

TABLE 2. Modal analysis data for Toby, Horsethief Creek, and Mt. Nelson sedimentary rocks. The approximate compositions given were derived from point counts of 158 thin sections with an average of 510 points per section. Standard deviation is given for lithologically grouped samples. Constituents represented by less than 1% are considered trace amounts (Tr)

	Approximate mean percent of each constituent:													
Lithology and location	No. of samples	Quartzite	Plutonic and gneissic	Sandstone	Mudstone	Carbonate	Undulose quartz	Polycrystalline quartz	Chert	Plagioclase	Untwinned potassic feldspar	Microcline	Opaques	Other (fine matrix and detritals)
Toby diamictite and argillaceous cgl. matrix:														
1) All samples	(77) –	9	Tr	3	3	8	13	5	2	Tr	Tr	Tr	1	56
± 1 std. dv.	–	13		5	8	3	9	10	3				1	21
2) Canal Flats and south	(10) –	5	Tr	4	2	6	18	2	2	Tr	1	—	1	59
3) Central Purcell Mts.	(31) –	8	—	3	4	13	14	2	2	Tr	Tr	Tr	Tr	53
4) Northern Purcell Mts.	(19) –	13	—	1	2	3	12	5	2	Tr	Tr	—	1	60
5) Western Purcell Mts.	(2) –	14	Tr	1	—	Tr	5	39	Tr	Tr	Tr	—	—	40
6) Boundary region	(11) –	10	—	1	5	4	13	13	Tr	Tr	Tr	—	Tr	54
7) Huckleberry Mts.	(4) –	3	—	Tr	4	10	16	1	4	Tr	Tr	—	1	61
Toby sandy conglomerate matrix:														
1) All samples	(12) –	30	—	1	4	5	13	31	2	Tr	—	—	1	12
± 1 std. dv.	–	23		3	10	8	9	23	5				2	8
2) Canal Flats and south	(1) –	24	—	—	Tr	—	30	29	Tr	Tr	—	—	4	13
3) Central Purcell Mts.	(2) –	36	—	—	2	12	22	11	6	—	—	—	1	9
4) Northern Purcell Mts.	(5) –	37	—	2	—	—	11	32	3	Tr	—	—	1	15
5) Western Purcell Mts.	(2) –	35	—	3	7	13	5	19	1	1	Tr	—	Tr	16
6) Boundary Region	(2) –	1	—	—	17	4	12	61	Tr	Tr	—	—	Tr	5
Toby silicious sandstone:														
1) All samples	(23) –	3	Tr	1	4	8	28	34	1	Tr	1	Tr	2	18
± 1 std. dv.	–	8		2	6	12	17	27	2		1		4	12
2) Canal Flats and south	(3) –	Tr	Tr	—	1	1	35	24	2	Tr	2	—	5	30
3) Central Purcell Mts.	(7) –	7	—	2	8	8	37	14	4	Tr	Tr	—	2	18
4) Northern Purcell Mts.	(6) –	2	—	Tr	3	3	33	37	3	Tr	—	—	2	17
5) Western Purcell Mts.	(1) –	—	—	—	7	36	13	43	—	Tr	—	—	—	1
6) Boundary Region	(6) –	3	—	1	1	12	11	57	—	Tr	1	Tr	Tr	14
Toby carbonate sandstone:														
Canal Flats area	(1) –	—	—	—	Tr	73	1	—	Tr	—	—	—	—	26
Sandstone clasts in Toby:														
All samples	(5) –	18	1	—	1	2	36	22	1	Tr	Tr	—	2	16
± 1 std. dv.	–	18	2		3	4	12	11	1				6	5
Quartzite clasts in Toby:														
All samples	(9) –	—	—	—	1	1	57	34	1	1	Tr	Tr	Tr	5
± 1 std. dv.	–				4	2	21	18	2	2				11
Mt. Nelson Formation:														
Quartzite	(8) –	—	—	—	Tr	Tr	36	56	Tr	Tr	—	—	Tr	7
± 1 std. dv.	–						23	24						13
Basal Horsethief Cr. Fm.:														
1) Pebble conglomerate matrix and sandstone	(15) –	19	4	Tr	Tr	1	27	26	1	2	1	Tr	1	18
± 1 std. dv.	–	26	7			4	19	12	2	2	1		2	14
2) Diamictite, Area 21	(3) –	25	—	—	2	5	16	12	3	Tr	—	—	1	35
± 1 std. dv.	–	22			3	9	7	11	4				1	19

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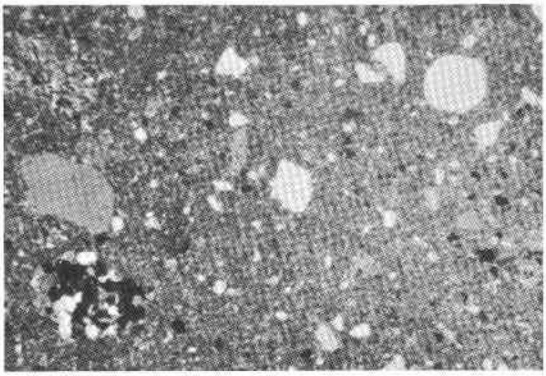

FIG. 10. Unmetamorphosed Toby Diamictite, 10X. Note the contrasting degrees of roundness of the various sized quartz grains, all contained in a clay-micrite matrix. Area 1.

albite (An 4–7), oligoclase (An 12), untwinned potassic feldspar, microcline, zircon, rutile, epidote, garnet, tourmaline, zoisite, clinozoisite, and muscovite (Table 2). Siliceous and heavy mineral grains are commonly subrounded to rounded. Other grains are subangular-to-subrounded. The composition of lithic grains is similar to that of larger clasts discussed earlier. Undulose quartz exists as angular-to-subangular very fine to medium sand, and subrounded-to-well rounded medium-to-coarse sand grains. The larger grains may contain mineral and aligned strain inclusions, and have clear, optically-concordant quartz overgrowths extending parallel to foliation. Polycrystalline quartz, the chief derivative of quartzite breakdown and a source for the angular undulose quartz sand, exists as subangular-to-subrounded, fine-to-coarse sand grains. Chert is commonly associated with carbonate and may form veins or patches in lithic carbonate grains. Authigenic opaque minerals include magnetite, hematite, goethite, leucoxene, pyrite, chalcopyrite, and graphite. All possible associations of clast and matrix compositions exist. However, a siliceous matrix generally contains a greater proportion of siliceous clasts and a calcareous matrix a greater proportion of calcareous clasts.

Diamictite–Regional Variations of Texture and Composition

A consideration of Figs. 12 and 13 demonstrates no marked regional variation in total distribution of clast size, or of maximum sizes present within the Toby Conglomerate. However, a slight clast coarsening is apparent to the north and east. A consideration of regional clast composition variation (Fig. 9) indicates a general homogeneous heterogeneity, with every diversity of composition present in every region. Slightly fewer carbonate clasts are present in the Northern Purcell Mountains and slightly more mudstone, slate, and phyllite clasts in the Boundary Region. Chert is genetically associated with carbonate and constitutes greater than 5% of clasts present in only the carbonate-rich Central Purcell Mountains. In the Canal Flats Region (area 2), granitic clasts are present in clusters within diamictite beds constituting up to 75% of clasts present. In areas paralleling the Rocky Mountain Trench, the Western Purcell Mountains and the Boundary Region they are present in trace amounts (Fig. 9; Table 2). Vein quartz exists everywhere in small amounts. Sandstone constitutes greater than 5% of clasts present in areas paralleling the Rocky Mountain Trench (areas 1, 2, 4, 5, 6, and 12). Badly weathered volcanic clasts are present in trace amounts in the Central Purcell Mountains and Boundary Region (areas 3, 7, 14, 22, 24, 25, and 26) and as an important (32%) constituent of basal Toby Conglomerate in area 11. In the Boundary Region and the Huckleberry Mountains, volcanic conglomerate of the overlying formations is similar in appearance to the essentially non-volcanic Toby Conglomerate. Although the formations are interstratified near their contact, there is no evidence that the volcanic formations were a Toby sediment source. Volcanic rocks generally overlie the Toby Conglomerate and, commonly being younger deposits, they could not have provided the severely weathered volcanic clasts found in some Toby exposures.

The constituents of megascopic diamictite matrix are without any systematic regional variation (Table 2). As would be expected, there is more carbonate and chert in the Central Purcell Mountains, more quartzite and polycrystalline quartz in the Northern Purcell Mountains, and more sandstone and granitic grains in regions adjacent to the Rocky Mountain Trench. A micritic matrix is most common in the Central Purcell Mountains. Elsewhere, matrixes commonly are quartz silt, clay, and their metamorphic equivalents.

Diamictite–Diagenetic and Metamorphic Effects

The effects of metamorphism on Toby diamictite are regionally variable. Most areas of the

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Canal Flats Region and the Central and Northern Purcell Mountains (excluding the westernmost exposures) have undergone only slight metamorphism. Although foliation commonly is developed, other alterations represent little more than an advanced stage of diagenesis. Pitting of quartz grains by solution and the development of overgrowths at points of least stress, the interpenetration of quartz grains, the replacement of quartz by carbonate where present, and partial recrystallization, dolomitization, and silicification are diagenetic alterations. The development of authigenic sericite, albite, carbonate, and traces of chlorite in scattered areas of these regions categorizes an approach to the greenschist metamorphic facies. Such changes are accompanied by the stretching and contorting of mudstone and micrite grains around more competent grains, and development of a mechanically induced fabric.

In the western part of the Central and Northern Purcell Mountains, the Western Purcell Mountains, the Boundary Region, and the Huckleberry Mountains, metamorphism has progressed to greenschist facies. Depending upon original composition, abundant muscovite, magnesium or iron-rich chlorite, albite, calcite, recrystallized quartz, and accessory epidote, apatite, tourmaline, and clinozoisite have developed in various Toby lithologies. More severe metamorphism in areas 21 to 26 is characterized by these minerals and accessory biotite, actinolite, sphene, and grossularite. Development of a lepidoblastic texture and extensive recrystallization complicates the distinction of original feldspar composition and detrital grains of quartzite, individual quartz types, chert, and carbonate (Fig. 11). Incompetent lithic grains are so stretched as to give the appearance of pseudo-lamination.

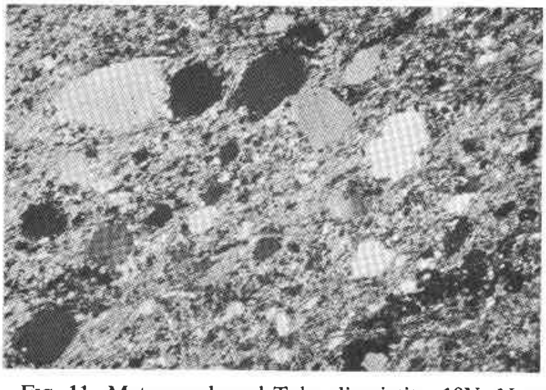

FIG. 11. Metamorphosed Toby diamictite, 10X. Note the prominent development of sericite and chlorite, a lepidoblastic texture, the pressure solution effects on large quartz grains transverse to foliation, and the fibrous extension of overgrowths and pressure fringes parallel to foliation. The trend of foliation is from the upper right to bottom left corners of the photograph. Area 24.

The fine microscopic matrix material of Toby diamictite probably is largely of primary origin. Diagenesis may have caused alterations of matrix material between chert, clay, and carbonate. However, the presence of feldspar grains retaining their original shapes and margins in lesser metamorphosed regions suggests that little matrix was added by grain deterioration. Cummins (1962) has noted that matrix may be produced by partial or complete disintegration of unstable minerals. However, the Toby Conglomerate was apparently derived from a mature source terrain and lacked such minerals in great quantity.

Wherever cleavage is extensively developed, clasts have become aligned with long axes lying with or without orientation in the plane of schistosity. Rotation of clasts which, by analogy with those in unmetamorphosed and unfoliated rock (areas 1 and 5) lacked primary orientation, was enhanced by the differential competence of the clasts and matrix of diamictite (Ramsay 1967, p. 221). Where extensive metamorphism has occurred, rotation was combined with stretching or fracturing, pressure dimpling, and opening of eyes at the ends of clasts (Figs. 5, 14). Stratification and foliation planes were projected and molded around clasts, sediment intrusions were stretched and bent and, very rarely, boudinage developed. Figure 15 demonstrates the probable effect of such alteration on quartzite clasts, which in some cases have been elongated by more than 50% (assuming these clasts in metamorphosed and unmetamorphosed regions had a similar original shape). This effect is more pronounced for carbonate and phyllite clasts, whose variations also reflect differences in original shape and competence. Phyllite clasts become so distended that they are hard to recognize in side view, although they are fragmented and spread out over much of the plane of foliation.

Conglomerate

Toby Conglomerate has a clast-supported framework and consists of two types. Conglomerate with an argillaceous or micritic matrix

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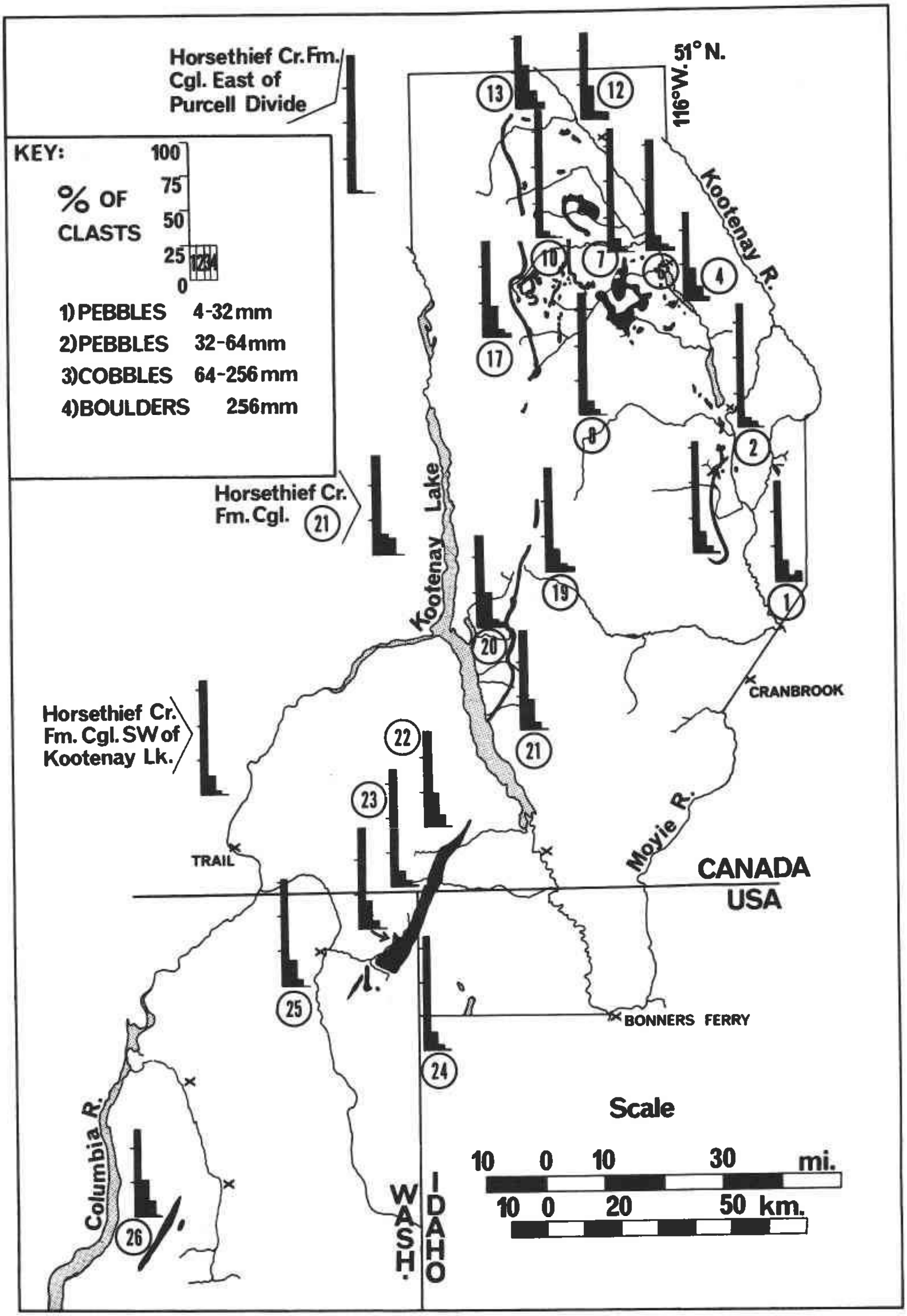

FIG. 12. Percentages of clasts in each of several size categories. Percentages for combined conglomerate and diamictite data are derived from measurement of 100 clasts per exposure, with an average of 6 size analyses for each of the regions indicated by number, arrow, or name. Small, medium, and large pebbles are grouped in the smallest size category. Horsethief Creek conglomerate data for exposures east of the Purcell Mountain divide include only pebble conglomerate.

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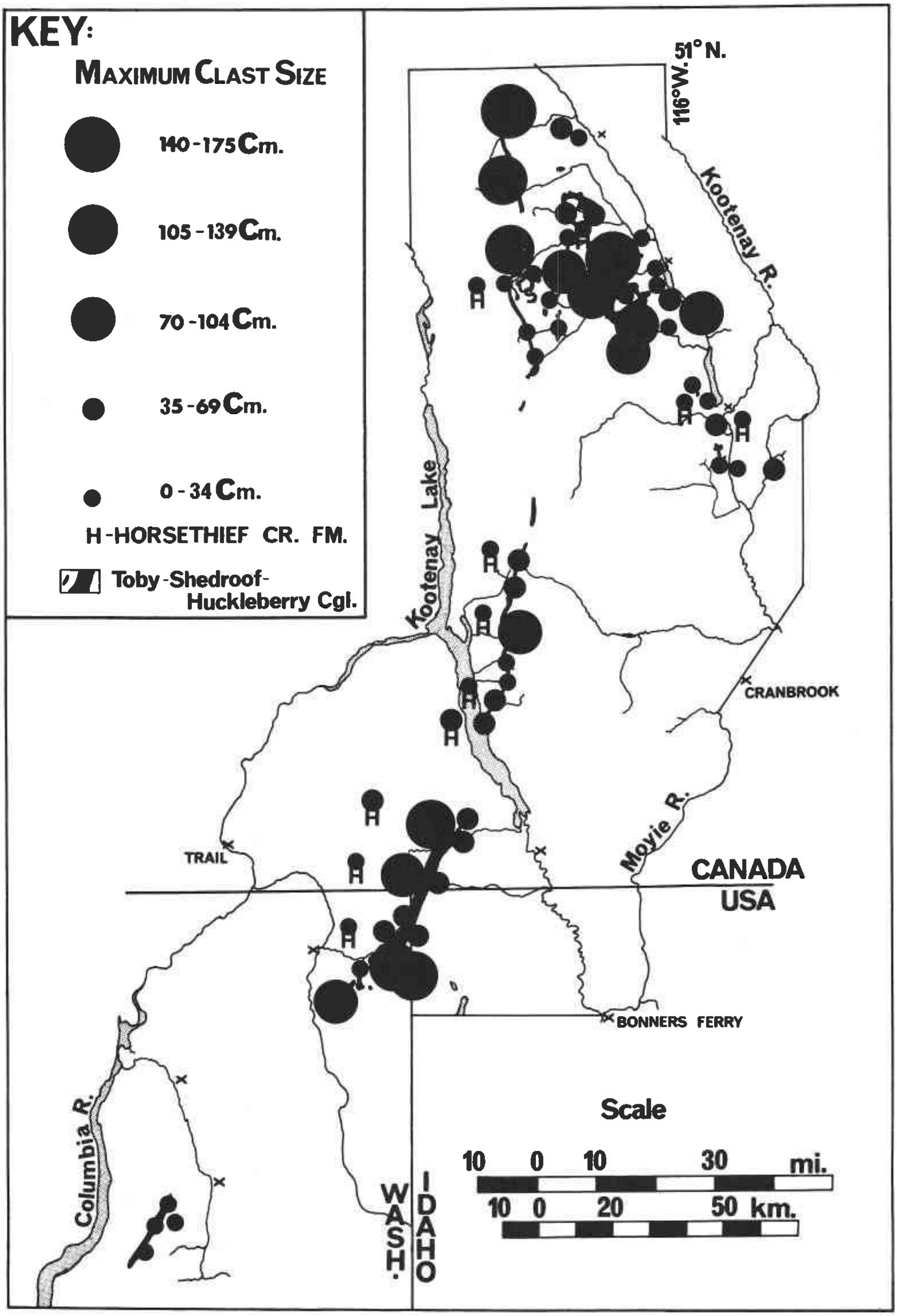

FIG. 13. Maximum clast sizes throughout Toby and Horsethief Creek exposures.

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has clast sorting, rounding, and size distribution similar to diamictite. It appears dark gray or brown with projecting resistant clasts. Clasts constitute 60 to 80% of the rock mass. Argillaceous conglomerate exists in lenses commonly one but up to 13 m thick and 5 to tens of meters long between masses of diamictite, argillite, or argillaceous sandstone (Figs. 6, 8), and in thick beds that commonly grade laterally into bedded diamictite (Fig. 8). Contacts of lenses are undulating and irregular, but those of beds are even and laterally persistent. Neither lenses nor beds contain apparent ordered fabric or primary structures.

The second conglomerate type has a coarse sand to grit matrix and poorly sorted, subangular-to-subrounded clasts. It is gray to brown and contains pebble-to-boulder-sized clasts constituting 65 to 80% of the rock mass. Sandy conglomerate forms steep-sided lenses 1 to 2 m thick and 2 to 5 m long. These may be within masses of diamictite (Fig. 16) or at the top of diamictite beds overlain by diamictite or argillite. It also forms 2 to 70 cm beds interstratified with diamictite or pebbly sandstone (Figs. 7, 8). Beds and lenses contain no primary structures or ordered internal fabrics other than rare crude size grading of clasts. In the Northern Purcell Mountain (areas 13 and 15) basal Toby strata consist of a 1 to 3 m bed of sandy breccia containing rounded quartzite and angular dolomite clasts, the latter derived from direct erosion of the underlying Mount Nelson Formation.

Clast size distribution and composition for both conglomerate types is similar to that of diamictites, and therefore is plotted with diamictite data in Figs. 9, 12, and 13. Matrix composition of sandy conglomerates is similar to that of diamictites, except that fine microscopic matrix is generally quartz silt (Table 2). Regional compositional variations of grains within sandy conglomerate matrix reflect those of diamictite. Extensive recrystallization in the Boundary Region and the resulting difficulty of distinguishing varieties of silicious grains has contributed to a probable overestimate of polycrystalline quartz in Table 2. Matrix composition of argillaceous conglomerates is identical to that of diamictite. Effects of tectonism and metamorphism on both conglomerate types are similar to those described for diamictite, except that closer packing of clasts contributes to more crushing, dimpling, stretching, and boudinage.

Sandstone

Pebby, gray to weathered-tan, coarse sandstone occurs in resistant beds commonly 0.1 to 0.7 m, but up to several meters in thickness. Beds are commonly interstratified with sandy conglomerates or fine sandstones (Figs. 6–8). They are laterally persistent, have even contacts, and generally contain no primary structures. Rarely they are faintly laminated. They may contain mudstone lenses less than 15 cm thick and 50 cm long, or have size grading within the bottom few centimeters of a bed.

Massive or laminated, gray to weathered-tan, fine- to medium-grained sandstone occurs in beds or as small lenses within diamictite. Beds average 5 to 30 cm in thickness and have even contacts. They are laterally persistent and are interstratified with all Toby lithologies (Figs. 6–8). Primary structures other than lamination are uncommon and include micro-crosslamina-

FIG. 14. Tectonic elongation of a clast. A dolomite clast elongated and rotated parallel to primary foliation. Bedding dips 50° to the left. Compare with Fig. 5. Note hammer on clast for scale. Area 22, 400 m east of Bayonne Creek along Highway 3.

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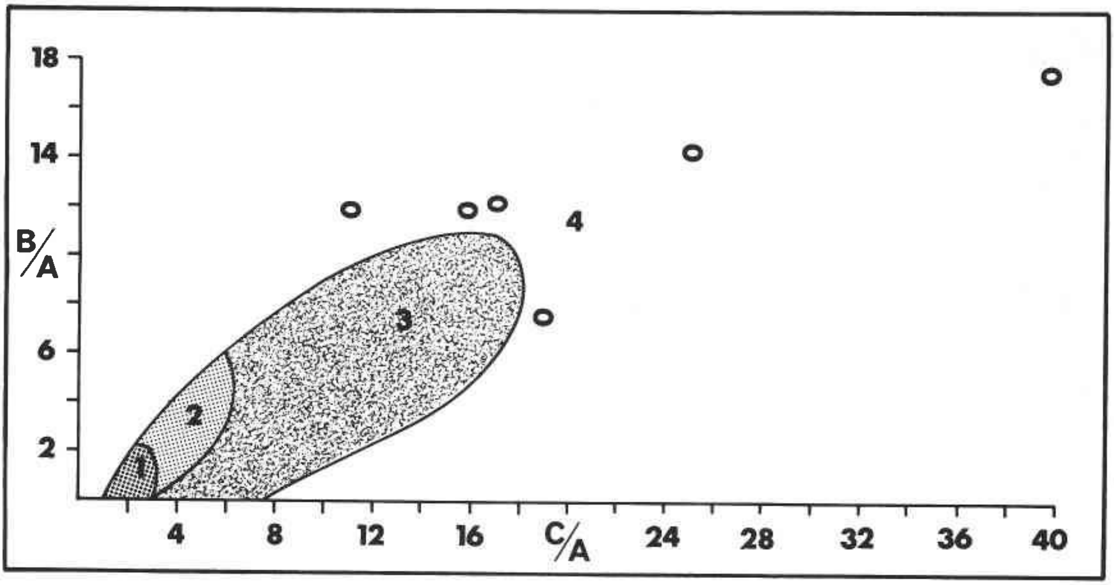

FIG. 15. Tectonic alteration of clast shape. Plotted ratios of the long (A), intermediate (B), and short (C) axes of clasts within Toby diamictite. Area 1 includes all quartzite clasts from relatively unmetamorphosed areas. Area 2 includes all quartzite clasts from exposures with pronounced chloritization of diamictite matrix. Area 3 includes all carbonate clasts from all regions. Area 4 includes phyllite and slate clasts from the areas with pronounced matrix chloritization. Data were obtained from 120 clast measurements.

FIG. 16. Toby sandy conglomerate. A steep sided lens of conglomerate with a sand and grit matrix marked out in black within a bed of massive diamictite, dipping 65° to the right. Area 23, on a ridge south of Monk Creek 1.1. km west of the confluence of Nun Creek and Priest River.

tions and small-scale climbing ripples, which, if present, overlie graded medium-to-fine sandstone and underlie laminated or featureless mudstone.

Among Toby sandstones there exists a complete gradation between moderately-to-well sorted quartz arenites and poorly-to-moderately well sorted quartz or lithic wackes. All sandstones contain occasional pebble to boulder clasts. Composition, texture, and diagenetic features of sandstones are similar to those described in

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diamictite matrix. However, more extensive grain intergrowth and deformation has occurred due to closer grain packing.

Fine-to-medium grained, gray-to-tan-weathering, dolomitized or recrystallized calcarenitic limestone contains a mixed aggregate of detrital micrite, oölitic micrite, dolomite, quartz and polycrystalline quartz grains and rare quartzite clasts. Beds average 0.5 to 2 m in thickness, have even contacts, are laterally persistent, and interstratified with all Toby lithologies (Fig. 8). Grains are typically subrounded and poorly sorted. A complete gradation exists between a quartz-lithic wacke with abundant carbonate grains and a micrite matrix and pure calcarenitic limestone. Diagenetic changes include recrystallization, silicification, and dolomitization, which operated at varying rates on grains and matrix. In highly metamorphosed areas carbonate has recrystallized to suffer a loss of all primary texture and appears as gray-to-white crystalline dolomite.

Argillite

The term argillite is generally applied to all Toby mudstone and sandy mudstone, regardless of composition, degree of metamorphism, or fissility. Argillite is gray, brown-weathering, and laminated or massive. It occurs in laterally-persistent, even-bounded beds 5 to 30 cm thick; thin laminated, massive, or rippled zones overlying graded sandstone within graded beds; and lenses within sandstone or diamictite (Figs. 6–8). Laminations are alternating light and dark gray, or red and dark gray. They may be depressed and punctured by or molded around single or clustered clasts (Fig. 17). Argillites consist of clay, micrite or quartz silt containing dispersed sand grains. Diagenetic alterations are similar to those of microscopic diamictite matrix.

Stratigraphy

There is little orderly vertical or lateral stratigraphic variation in texture, composition, thickness, or association of lithologies within the Toby Conglomerate. Beds of any composition may be interstratified at any horizon. However, in most sections of nonvolcanic areas, basal beds are predominantly diamictite, mid-sections contain a more complex interstratification of all lithologies, and upper parts of sections contain chiefly argillites and fine sandstones, typically with graded beds and isolated clasts (Figs. 18, 19). Within the Boundary Region beds tend to be thinner and lithologies more mixed than elsewhere (Fig. 8). Here alternating diamictite conglomerates and sandstone beds only 3 to 10 cm thick and lenticular masses of conglomerate and sandstone are more common than in the Purcell Mountains.

There are no consistent correlations between clast size distribution, maximum clast size, gen-

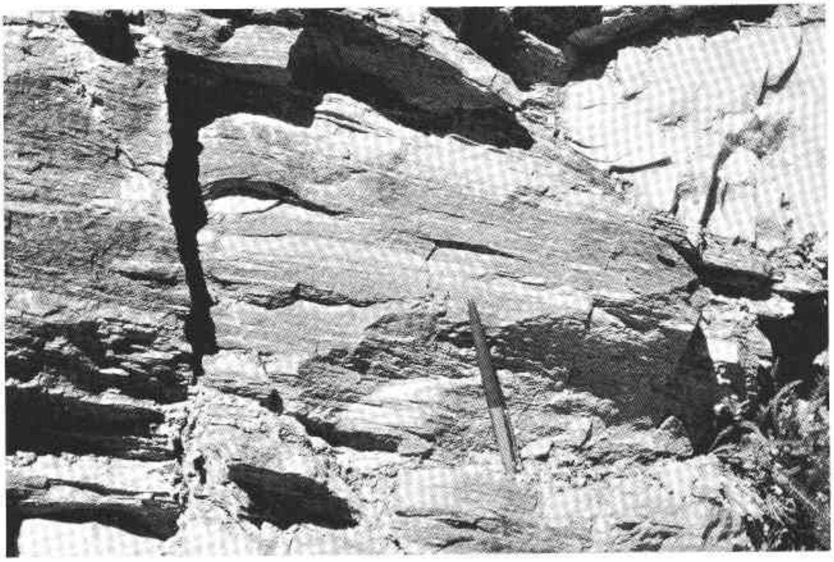

FIG. 17. Toby laminated argillite. Argillite with alternating red and black laminations containing pebbles and boulders of dolomite. Note the molding of laminations around clast in center and the depression of laminations under large clast in upper right. Area 24, along Pass Creek Pass Road.

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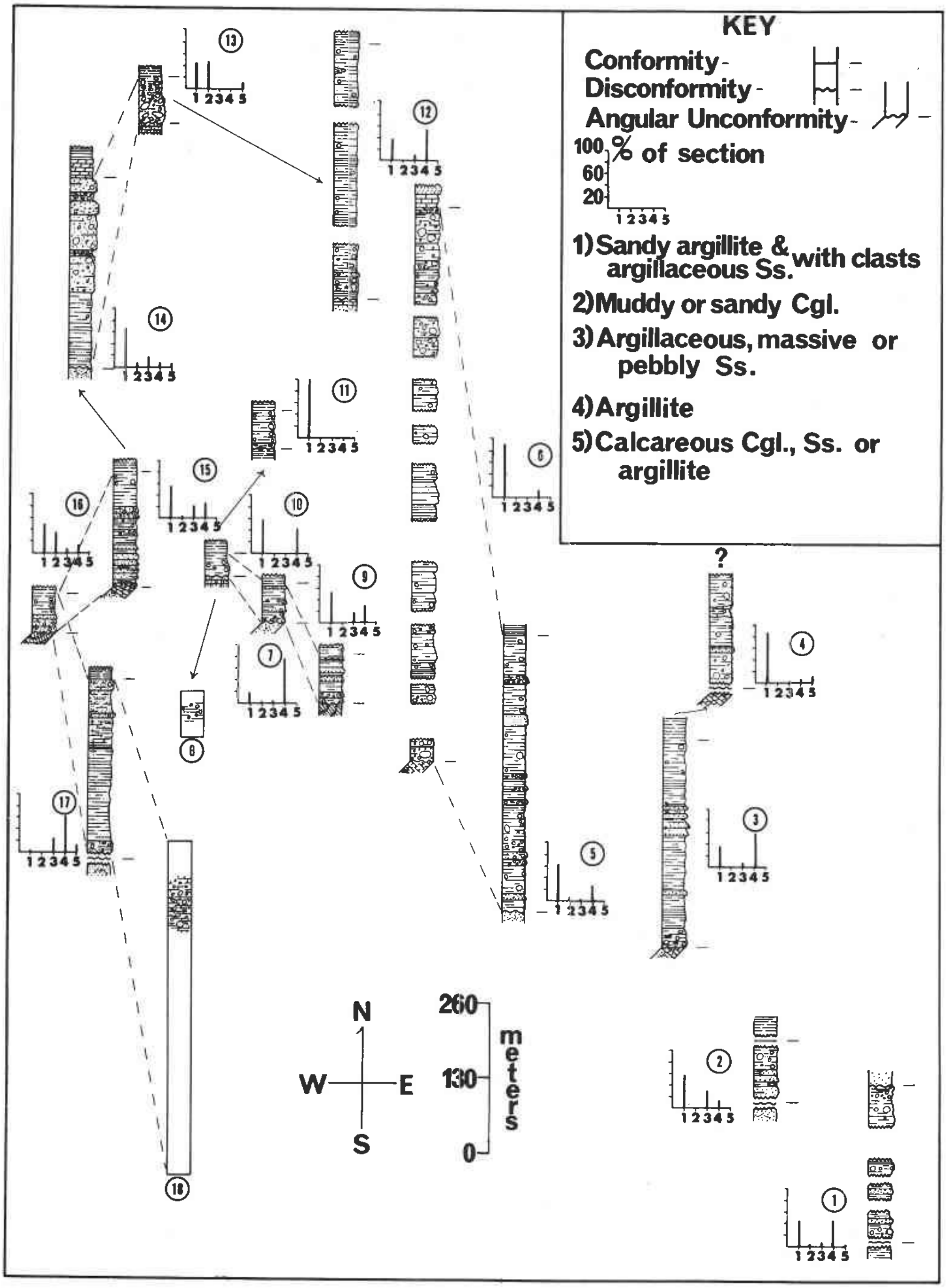

FIG. 18. Stratigraphic variations of the Toby Conglomerate: canal flats region, central, and northern Purcell Mountains. Generalized stratigraphic columns show only principal lithologic changes. Bar graphs show percentages of various lithologies within their sections. Contacts are placed at traditional stratigraphic boundaries used by previous workers. The Horsethief Creek Group overlies the Toby Conglomerate in all areas but number 1, where Cambrian quartzite overlies a disconformable contact. Thicknesses for sections 8 and 18 are taken from Walker (1926, p. 9). Dashed lines correlate sections connected by continuous rock exposure. Arrows indicate sections which lie directly along strike of each other yet are unconnected by continuous rock exposure. Numbers refer to locations on Fig. 1 and sections are placed in their approximate geographic positions.

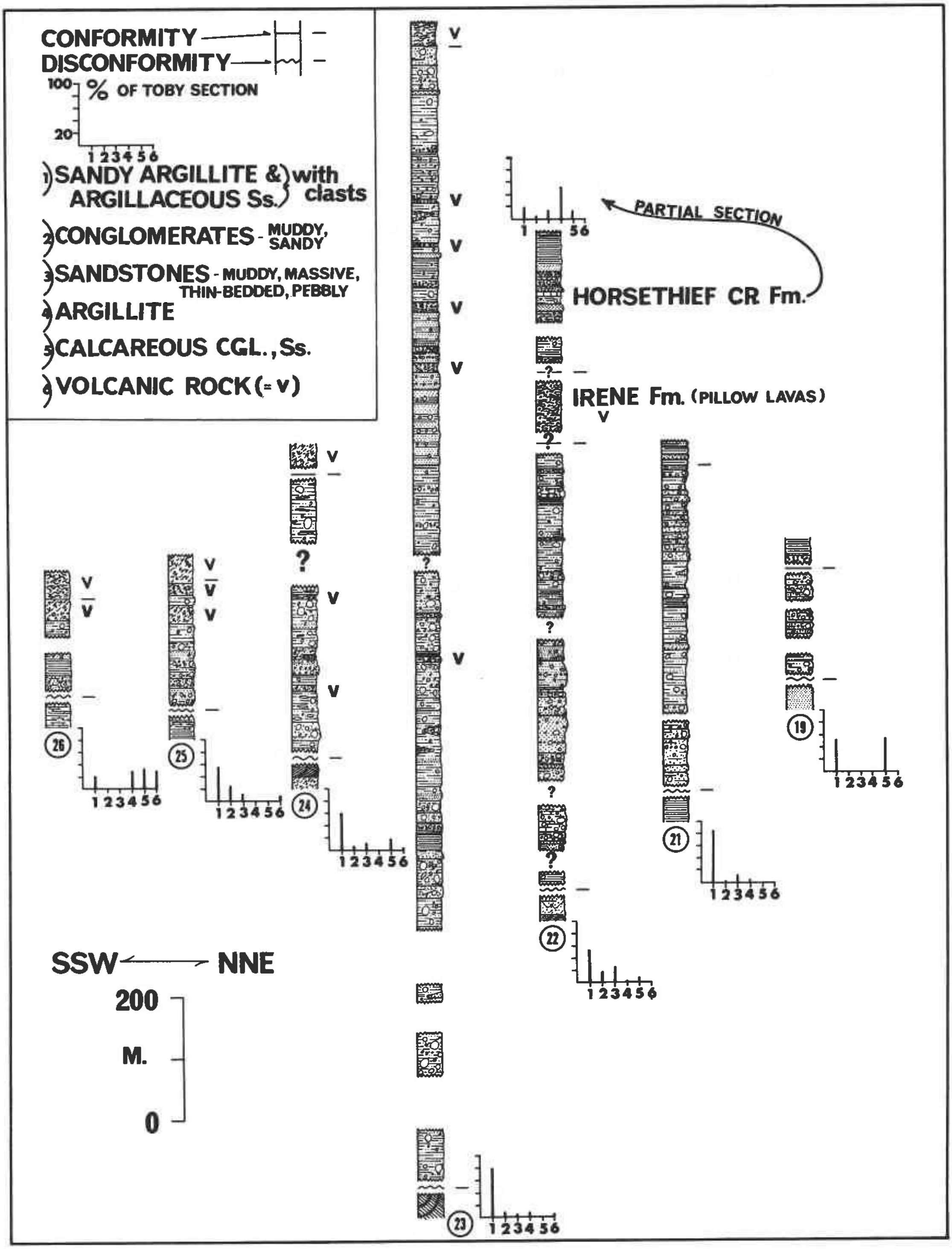

FIG. 19. Stratigraphic variations of the Toby Conglomerate: boundary region, western Purcell, and Huckleberry Mountains. Generalized stratigraphic columns show only principal lithologic changes. Bar graphs show percentages of various lithologies within these sections. Contacts are placed at traditional stratigraphic boundaries used by previous workers. Numbers refer to locations given on Fig. 1; sections are placed in their approximate geographic positions.

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eral lithologic coarseness of a section, and section thickness. Sections at areas 2, 13, 15, 16, 19, and 22 have the greatest quantities of coarse conglomerate and sandstone (Figs. 18, 19), yet in most cases lack the coarsest overall clast-size distributions and maximum sized clasts (Figs. 12, 13). If the top of the Toby Conglomerate approximates a time datum, the formation has remarkable lateral thickness variation with areas 6 and 23 showing the greatest sediment accumulation.

Exposed basal Toby contacts are either concordant disconformities or angular unconformities with discordances as great as 30° (areas 9, 12, and 15). Contacts are always irregular and defined by sharp contrasts in lithology. Upper Purcell strata are in most cases overlain by pebbly laminated argillite or diamictite. As evidenced by a scarcity of clasts, a high degree of clast roundness or a disparity between clast and underlying bedrock lithologies, this sediment was apparently derived from a distant source. Only between 13 and 15 and in the vicinity of area 11 (Reesor 1957*a*), is there evidence of contemporaneous erosion and deposition. Here a bed of breccia, composed of rounded transported and angular bedrock clasts, separates wholly transported diamictite and Mount Nelson dolomite.

In most areas of the Purcell Mountains, the Toby Conglomerate is conformably overlain by argillites, sandstones, conglomerates, or carbonates of the Horsethief Creek Group. The contact is traditionally placed at some marked change in lithology and/or where diamictite ceases to be a common lithology. Thus in a general sense it represents a cessation of Toby depositional conditions yet is not clearly defined by a consistent lithologic sequence. In most areas the contact is placed arbitrarily because rare beds of diamictite, representing a sporadic continuance of Toby conditions, are present interstratified with typical basal Horsethief Creek lithologies well above the major mass of diamictite.

In the Boundary Region and Huckleberry Mountains, the Toby Conglomerate is conformably overlain by volcanic greenstones. Placing of the contact is complicated by interstratification of nonvolcanic diamictite and thin volcanic greenstones, agglomerates, breccias, and conglomerates near the top of any Toby section (Fig. 19). Although the Toby Conglomerate is terrigeneous in derivation, it is most convenient to include the rare thin zones of these contemporaneous volcanics within Toby sections, and to place the formation contact where thick sequences of greenstone overlie diamictite.

Huckleberry, Leola, and Irene Volcanics

Introduction

Thick volcanic greenstones of the Huckleberry Greenstone and Leola Volcanics in northeastern Washington (Areas 24–26) and the Irene Volcanics in British Columbia (Areas 22–23) conformably overlie the Toby Conglomerate. These consist of several volcanic lithologies, similar throughout these regions.

Composition and Fabric

Huckleberry, Leola, and Irene volcanic rocks are foliated and altered andesitic greenstone, tuff, breccia, agglomerate, and volcanic conglomerate. Drab dark greenstone units may display vesicle or pillow structures. Pillows are olive green and separated by dark green, friable chlorite schist.

Thin beds of alternating laminae of green vitric-lithic tuff and chloritized ashy mud are interstratified with other volcanic lithologies. Vitric grains have bubble wall shard structures. Intermixed lithic grains are micro-crystalline pumices compositionally similar to the greenstone.

Volcanic breccia and agglomerate both are composed of poorly sorted, contorted clasts of andesite in a chlorite schist matrix. Breccia clasts are angular, closely packed, and contained in lenses which never exceed 1 m in thickness and 5 m in length. Agglomerate consists of subrounded, dispersed clasts contained in meter-thick beds with uneven contacts. Both are associated with all volcanic lithologies.

Volcanic conglomerate is composed of poorly sorted, closely packed-to-dispersed, subangular-to-subrounded clasts of detrital sedimentary and volcanic pebbles to boulders in a chloritic matrix. It is commonly interstratified with diamictites lacking volcanic clasts near the top of Toby sections in areas 22 to 26. Beds are even-bounded, laterally persistent, and lack ordered internal fabric. Volcanic clasts constitute half of those present, are compositionally similar to Windermere greenstones, and probably were derived penecontemporaneously from sites of early volcanism. Terrigeneous clasts are similar to those

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in surrounding diamictite. Matrix consists of quartz silt, sericite, and chlorite and may in part have been derived from ashy muds.

Stratigraphic Variations

In Washington the Huckleberry Volcanics are beveled and overlain unconformably by the Lower Cambrian Addy Quartzite. In the Boundary Region the Leola and Irene Volcanics contain occasional lenticular masses of non-volcanic diamictite and dolomite up to 30 m thick and 300 m long (Daly 1912, pp. 143–144; Rice 1941, pp. 15–16). The greenstones are conformably overlain by a thick zone of diamictite largely lacking volcanic clasts. It is considered to be the basal Monk Formation on Horsethief Creek Group, suggesting that Toby conditions of deposition existed throughout a period of volcanism that did not effect the source area of diamictite clasts.

The Basal Monk Formation and Horsethief Creek Group

Introduction

The completely conformable nature of the contact between the Horsethief Creek Group and the Toby Conglomerate in the Purcell Mountains suggests that a description of Horsethief Creek and Monk lithologies might contribute to the understanding of the Toby Conglomerate.

Pebble Conglomerate

Light gray to tan-weathering, well sorted, close packed pebble conglomerate with a gritty sandstone matrix contains well rounded clasts (4 to 5 on Powers scale) resembling closely packed ball bearings (Fig. 20). Beds are commonly 0.5 to 2, but up to 18 m thick, even-bounded, and laterally persistent. They are interstratified with argillite, slate, and sandstone. Lenses are commonly less than 1 m thick and 15 m long, have uneven contacts, and are present within argillite and fine sandstone beds. Pebbles constitute an average of 75% of the rock mass. The high degree of clast sorting is reflected in the predominance of pebble-sized clasts and small maximum clast-size of Horsethief Creek conglomerate. (Figs. 12, 13). Beds and lenses are commonly massive, but may contain basal ripups derived from underlying argillite, and may show crude size grading in their top several centimeters.

Pebble conglomerate contains an average of 97% gray to white quartzite and vein quartz, 2% gray-to-weathered tan crystalline dolomite, and traces of weathered quartz arenite, white or black chert and slate. Grain and matrix composition, texture, and diagenetic alteration are similar to those discussed for Toby diamictite (Table 2).

FIG. 20. Horsethief Creek Pebble Conglomerate. Close-packed, well sorted, quartz pebble conglomerate of the Horsethief Creek Group. Area 9, along Law Creek trail 1.1 km from the confluence of Law and Slade Creeks.

Sandstone

Light gray to tan-weathering, pebbly sandstone occurs in evenly-bounded, laterally persistent beds commonly 0.2 to 1.5 m thick. Bedded sandstone may be well sorted and massive, poorly sorted and pebbly, laminated, or crudely graded (Fig. 21). Uncommon sedimentary structures include oscillation and current ripple marks and tabular cross strata in sets 10 to 15 cm thick. Coarse sandstones are interstratified with argillite, dolomite, and pebble conglomerate. They are better sorted than the matrix of pebble conglomerate, and contain fewer quartzite grains, but are otherwise similar in composition.

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FIG. 21. Horsethief Creek coarse graded bed. Bed contains a basal zone of graded pebbly coarse sandstone overlain by medium-grained sandstone with faint laminations. Note the lack of persistence of cleavage through the coarser part of the bed from the overlying laminated sandstone to the underlying argillite. Area 7, 1.2 km up road to Paradise Mine.

Gray-to-tan-weathering, massive or laminated, fine-to-medium-grained sandstone occurs in 2 to 30 cm thick beds interstratified with argillite or slate. It is commonly laminated or graded. Repetitiously graded beds may have sharp basal contacts consecutively overlain by graded medium-grained sandstone, laminated fine-grained sandstone, ripple drifted siltstone, and laminated to unlaminated mudstone. This sequence is rarely complete. Typically, the graded sand is overlain either by only the laminated and rippled zones or the mudstone (Fig. 22). In unmetamorphosed regions, similar beds may be found within upper parts of the Toby Conglomerate.

Slate and Argillite

Thick sequences of laminated slate and argillite

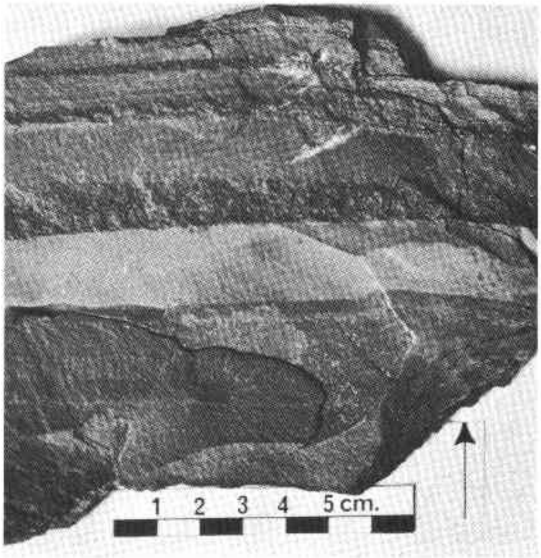

FIG. 22. Incomplete graded beds. Graded medium-to-fine sandstone abruptly overlain by massive or laminated mudstone, typical of the upper Toby Conglomerate and basal Horsethief Creek Group. Area 7.

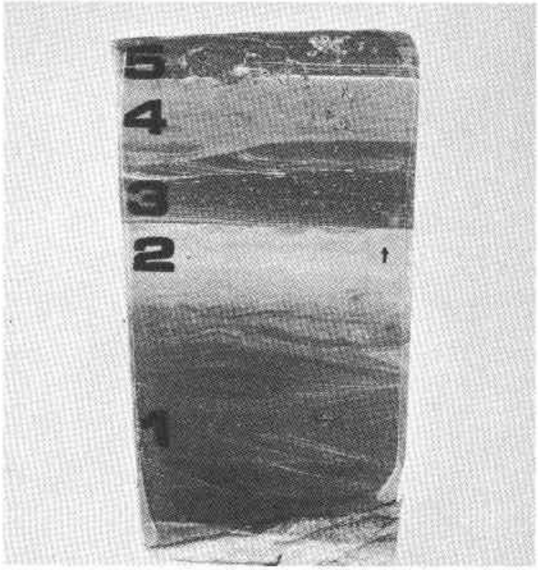

FIG. 23. Horsethief Creek laminated argillite.
Note: (1) Basal zone of ripple cross laminated and drifted silt abruptly overlying unlaminated clay.
(2) Zone of clay with vague size grading and laminations.
(3) Zone of varve-like alternating laminae of coarse silt and clay with basal load structures, overlain by micro-cross laminated silt.
(4) Zone of vaguely laminated and rippled clay.
(5) Top zone of varve-like alternating laminae of silt and clay. Arrow 2.5 mm long. Area 2.

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and mudstone are composed of clay, micrite, or quartz silt. They are interstratified with sandstone and pebble conglomerate. Beds may be structureless or exhibit delicate grading, ripple-drifting, and lamination (Fig. 23).

Carbonate

Light gray-to-tan-weathering, laminated or massive limestone exists in lenticular masses among beds of sandstone and pebble conglomerate. Lenticular masses are commonly 0.5 to 3 m in size oriented parallel to stratification, but may exist in mappable units up to 20 m thick and several hundred meters long (area 2). Top and bottom contacts are sharp but undulating, and show no gradations of lithologies. However, they grade laterally to meter-thick breccia zones of mixed angular chunks of dolomite and rounded quartz pebbles held in a carbonate matrix. In turn this zone grades into surrounding pebbly coarse sandstone. Recrystallization, dolomitization, and silicification have destroyed diagnostic primary fabric. However, these masses are thought to have been biogenetically produced. Evans (1933, p. 118) reported finding the algal stromatolite *Newlandia* within similar carbonates higher in the Horsethief Creek Group.

White-to-gray crystalline dolomite occurs in even beds 1 to 3 m thick interstratified with all varieties of Horsethief Creek lithologies (Figs. 18, 19). Distinction of detrital intraclasts within lesser recrystallized samples suggests that these may have been calcarenitic limestones prior to alteration.

Diamictite

Diamictite like that of the Toby Conglomerate is not typical of the Horsethief Creek Group. It does occur interstratified with typical lithologies within the contact zone of the two formations. In the Purcell Mountains such beds are thin and rare. In the Boundary Region, however, the basal Monk Formation and Horsethief Creek Group contain approximately 60 m of diamictite overlying the volcanic formations (Fig. 19). Here clasts are subrounded (3.5 on Powers scale), poorly sorted (Figs. 12, 13), and constitute 20% of the rock mass. Beds are 1 to 10 m thick and are interstratified with argillite, sandstone, and carbonate-rich conglomerate. Lenses of diamictite and argillaceous conglomerate similar to those within Toby argillite exist within argillite found in Horsethief Creek.

Diamictite of the Boundary Region contains an average of 15% quartzite, 82% carbonate, 2% mudstone and slate, and a trace of granitic clasts, all similar to those of the underlying Toby Conglomerate, and few clasts of volcanic greenstone derived from the underlying volcanic formations.

Stratigraphy

The existence of a thick zone of diamictite overlying greenstones and marking the base of the Monk Formation and Horsethief Creek Group in the Boundary Region was recognized by Little (1950, p. 8), Rice (1941, pp. 18–19), and Walker (1929, p. 125A; 1934, p. 7). Elsewhere, however, the basal boundary of the Horsethief Creek Group is placed at the top of abundant diamictite within the stratigraphic sequence. Thus there is inconsistency in stratigraphic criteria employed in defining formations over the entire region of Winderemere exposure. For consistency, the Toby – Horsethief Creek contact should be placed some 60 m above the volcanic formations of the Boundary Region. Here diamictite ceases to be dominant and is succeeded by argillite, sandstone, pebble conglomerate, and dolomite. This boundary would mark the cessation of Toby depositional conditions as it does in the Purcell Mountains. The volcanic units, which contain masses of diamictite, would become members of the Toby Conglomerate.

Paleogeography and Sediment Sources

The East Kootenay orogeny is thought to have formed a landmass which has been called "Montania" and which extended to the vicinity of the present Purcell Mountains (Deiss 1941, p. 1097; Reesor 1957*b*, p. 151). To the south and east of present Windermere exposures Lower Cambrian quartzites rest directly upon Upper Purcell strata. Montania may have remained exposed here throughout Windermere time and probably adjoined the Canadian Shield as a peninsula (Fig. 24).

Montania provides a logical source for much of Windermere sediments. The clasts and mineral grains which constitute the bulk of those present in the Toby Conglomerate are lithologically, compositionally, and texturally similar to those of the Upper Purcell System (Table 2). The abundance of polycrystalline quartz compared with undulose quartz in bedded quartzite versus

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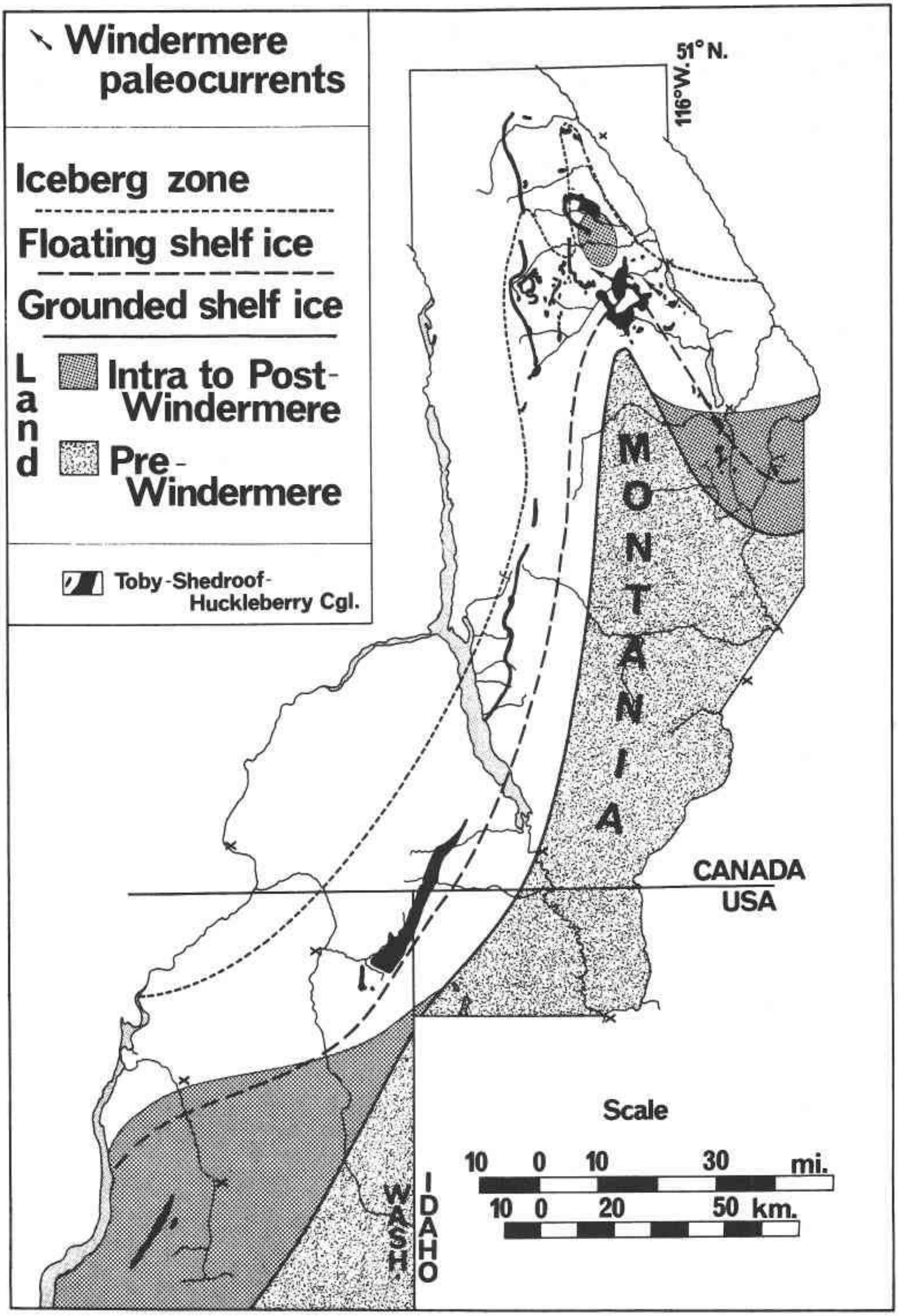

FIG. 24. Windermere paleogeography and ice distribution. A hypothetical restoration of Windermere paleography and distribution of glacial ice during the period of Toby deposition. Note the intra- and post-Windermere additions of land, which are today reflected by the presence of Windermere–Cambrian unconformities produced by intra-Windermere tectonism. Paleocurrent data was obtained only in the Central Purcell Mountains. The configuration of Montania is based largely upon Deiss (1941) and Reesor (1957) and does not account for post-Windermere structural dislocation.

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quartzite clasts may be ascribed to the varying effects of post-Windermere tectonism on bedded quartzite as opposed to matrix-cushioned clasts. The Horsethief Creek Group becomes finer-grained west and north of the Boundary Region and Purcell Mountains, thus was derived from an eastern source (Reesor 1957*b*, p. 161; Walker 1926, p. 15). The embayment on the east side of Montania (Fig. 24) would logically receive both eroded Upper Purcell sediment debris from the west and cratonic debris from the east. But as Lower Cambrian seas transgressed over most regions of Windermere exposure, quartz arenite derived largely from the craton blanketed rocks of the Windermere System. Such derivation is suggested by compositional maturity (Campbell *et al.* 1962, p. 62; Deiss 1941; Leech 1954, p. 7; Little 1950, p. 13) and paleocurrent directions (Mountjoy and Aitken 1963, p. 167).

A cratonic source is postulated for less common clasts of granite and granite gneiss and probably a part of the sandstone, well-rounded quartz, and feldspar grains within the Windermere System. Granitic stocks formed during the East Kootenay orogeny are compositionally dissimilar to granitic clasts found throughout the more eastern exposures of the Toby Conglomerate and it is questionable that the stocks could have been unroofed soon enough after formation to provide a source for Toby detritus (Leech 1962*a*, p. 6). No evidence exists that East Kootenay deformation was sufficiently strong to produce gneissic masses (Leech 1962*a*, p. 6; Reesor 1957*b*, p. 161). Thus one must look to the Hudsonian cratonic rocks for a source of granitic clasts. The problem remains of how quantities of boulder-sized clasts could be carried to Canal Flats (Area 2), an area which probably was some distance from source rock that now underlies the plains of western Alberta (Reesor 1957*b*, p. 162). Recycled sedimentary rocks overlying the holocrystalline cratonic terrane could provide a source for sandstone and well-rounded quartz grains now found in the Windermere System largely among the Rocky Mountain Trench, and for the variety of feldspar types within Horsethief Creek sandstones.

Clasts of weathered andesite in areas 7 and 11 could have been derived from local masses of Upper Purcell volcanic rock. Reesor (1957*a*) found Toby Conglomerate with a vesicular lava matrix in area 14, which suggests proximity to a local volcanic erosional high. An obvious source of diamictite matrix would be a thick mantle developed on the craton. The problem of probable long transport distance from the craton of part of the ill-sorted sediments found in the Windermere System and the fact that the maximum-size clasts, coarsest clast distributions, and coarsest Toby sections are not always those nearest potential source areas requires an uncommon depositional situation.

Depositional Mechanisms and Environment

Earlier Interpretations

Walker (1925, p. 225A; 1926, p. 15) and Rice (1941, p. 23) presented the original field interpretations of genesis of the Windermere System, which have since been cited without substantial modification. Walker envisioned the Toby Conglomerate as having been deposited in subsiding basins bordering a high-relief landmass, perhaps a piedmont fanglomerate deposited along a fault scarp. The Horsethief Creek Group was then formed as the sea transgressed into these basins and reworked sediments continually derived from Montania. Sea level fluctuations produced the seemingly aberrant associations of interstratified argillite and pebble conglomerate. Rice recognized the Toby Conglomerate to be a blanket deposit whose considerable geographic extent seemed to prohibit the fanglomerate mode of genesis. Rather, he thought it was produced as the sea transgressed and reworked terrestrial gravel deposits on gently folded Upper Purcell rocks. As relief was reduced and sea level rose, Horsethief Creek lithologies were produced as rivers transported finer sediment to the sea. Neither interpretation successfully explains Windermere lithologic associations since neither adequately explains the formation of large quantities of diamictite.

The Formation of Diamictite

To interpret the origin of the Toby Conglomerate, I shall first consider the predominant diamictite. Its volume and extent, textural bimodality and abundant matrix require either that clasts and matrix were separately deposited, or were transported to the site of deposition by a viscous medium lacking a selective sorting capability. Depositional mechanisms that satisfy these qualifications are numerous (Flint 1961, p. 150). As noted below, the associated lithologies, com-

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positional diversity, age, history of diagenesis, and great lateral extent of the Toby Conglomerate at once exclude all but subaqueous mass flow, glacial marine sedimentation, or both.

Environmental factors favorable to the formation of terrestrial mudflows associated with alluvial fan deposits probably were operative on Upper Proterozoic landmasses. However, the absence of leveed channels and marginal debris piles, surface mudcracks and weathered zones, overlying lag gravels, and associated sand and gravel alluvial deposits with pronounced tractive current structures and channeling precludes this mode of origin (Blackwelder 1928; Sharp and Nobles 1953). Moreover, terrestrial mudflow deposits rarely constitute more than 10% of a fan or exceed a meter in thickness, and should exhibit rapid and consistent lateral textural changes (Blissenbach 1954). Diamictite constitutes over 50% of the Toby Conglomerate and consistent facies relationships characteristic of fans are lacking.

Diamictite may also be formed by terrestrial glacial wasting, but should be associated with high-energy outwash sediments preservable in the geologic record. Terrestrial tills should seldom exceed 100 m in thickness (Flint 1961, p. 142). The Toby Conglomerate lacks high-energy sedimentary features and in several areas is well over 100 m thick.

The presence of pillow lavas and Horsethief Creek carbonate suggest that the basal Windermere System was indeed subaqueous. The presence of laminated argillites and sandstones lacking strong tractive current features suggest that the basal Windermere System was deposited in a low energy environment. Its paleogeographic position and widespread nature suggest that this series was marine.

The difficulty of distinguishing non-glacial mass flow and glacial marine deposits on the basis of diamictite texture, fabric, and association with normal marine sediments has been stressed by Crowell (1964; Crowell *et al.* 1953). He believes that final conclusions must be based upon consideration of diamictite fabric combined with study of paleotectonics, paleogeography, paleoclimatology, sediment sources, and associated abnormal marine sediments. Such analysis has led to the reinterpretation of numerous "tillites" as non-glacial submarine mudflow deposits (*e.g.* Dott 1961). Similar analysis of the Toby Conglomerate in Table 3 demonstrates that a completely non-glacial, submarine mass-flow model must be discarded.

Glacial Marine Sedimentation: Historical Perspective

Pleistocene glacial marine sedimentary deposits are characterized by a diversity of intermixed tillite, density-flow, and normal-marine deposits. They include many of the features associated with the Toby Conglomerate, such as thick interstratified tabular and lenticular diamictites, argillaceous conglomerate, sandy conglomerate, massive coarse sandstone, laminated fine sandstone, calcarenitic limestone, graded sandstones, and laminated mudstone, all containing isolated boulders. Excellent analogues for the Toby depositional environment postulated below include near-shore North American glacial marine deposits described by Armstrong and Brown (1954) and Miller (1953).

Confirmed ancient tillites contain similar features, but are best distinguished as glacial by the presence of abundant dropped stones in thinly-bedded sequences (Frakes and Crowell 1967; Schwarzbach 1963). The best descriptive and all-inclusive model for glacial-marine sedimentation is that developed by Carey and Ahmad (1960) from modern Antarctic ice shelves. This was revised by Reading and Walker (1966) to apply to an Upper Proterozoic situation (Fig. 25). The latter will be utilized in a discussion of the Windermere System.

Glacial Marine Sedimentation of the Basal Windermere System

Glacial marine sedimentation is a viable alternate hypothesis to those presented earlier concerning the genesis of the basal Windermere Series. It best explains the composition, fabric, and stratigraphic associations and variations within these rocks, and therefore will be utilized in reconstructing a probable environment of deposition of the Basal Windermere System.

Prior to the deposition of the Toby Conglomerate, and undulating low-relief peninsular landmass, Montania, existed in the region of the Purcell Mountains. It was covered with a thin veneer of weathered mantle and terrestrial sedimentary debris (Fig. 26, Stage 1). With the advent of a Late Precambrian ice age, I postulate that dry-based continential glaciers flowed from the craton westward over Montania. In the

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TABLE 3. Submarine mass flow vs. glacial marine sedimentation. Evidences presented are those critical to the acceptance of a glacial versus a non-glacial model. Other stratigraphic, compositional and textural features described previously and not listed above may be ascribed equally to either model.

Evidence	Non-glacial submarine mass flow	Glacial marine sedimentation
1. Presence in all areas of clasts derived from the craton; especially coarse and abundant in area 2.	Difficult to explain probable long distance of transport.	Expected.
2. Absence of striated or faceted stones.	Expected.	Possible, because most clasts have been subjected to tectonic alteration and are hard to separate from the matrix, and because such features are found on less than 10% of Pleistocene stones and on no crystalline clasts of the British Pleistocene (Flint 1957; Spencer 1968).
3. Clasts distinctly clustered within some diamictite beds.	Difficult to explain.	Expected from local rafting of clasts laden ice (Ovenshine 1970).
4. Single or clustered megaclasts in massive sandstones and thinly bedded fine sandstones and argillites. Depressed and punctured laminations under clasts where foliation is not pronounced.	Difficult to explain.	Expected, from ice rafting over current deposited sediments.
5. No consistent correlations among maximum clast size, clast size distribution, position in bed or section, thickness of bed or section, over-all coarseness of section and geographic location.	Sections with maximum size clasts and greatest overall coarseness should be nearest potential source areas. (Although it is true that, due to steep dips, gradations of sediment type basinward are not well portrayed.)	Expected.
6. Very thin (less than 10 cm) alternating beds of diamictite and sandy conglomerate; or argillaceous conglomerate and pebbly sandstone.	Not characteristic of mudflow units.	Expected, from separate sporadic effects of density flow, melting and dropping and bottom current winnowing.
7. Lenticular, in places vertical-sided, masses of sandy conglomerate within diamictite.	Possible, by scour in cohesive sediments.	Possible, similar to features produced in subglacial meltwater channels (Frakes and Crowell 1967), or by ice rafting into soft sediment (Ovenshine 1970).
8. Uncontorted lenses of sandstone within diamictite beds.	Impossible to explain, unless they reflect unrecognizable bedding planes.	Possible, produced by flow of subglacial meltwater.
9. Absence of load structures, contorted stratification, content grading, and mudstone ripups in thick diamictite. Absence of obvious slump deposits associated with thick diamictite.	Possible.	Expected, by direct subglacial deposition of till.
10. The Upper Purcell – Toby unconformity commonly overlain by diamictite.	Unlikely that in most regions diamictite should rest directly on unconformity.	Possible, if ice initially scoured to a bedrock surface and then melted.
11. Wide geographic distribution of Toby diamictite.	Unlikely.	Expected, should continental glaciers move westward from the craton.
12. Toby Conglomerate deposited in tectonically unstable region.	Possible, tectonic instability conducive to formation of mass flow deposits.	Possible, Precambrian tillite would more likely be preserved among thick sediment prisms reflecting tectonic instability.

region of Toby deposition glacial ice scoured surficial land and littoral deposits. The ice probably isostatically depressed the Montania coastal zone producing an unweathered rock surface overlain by grounded shelf ice (Fig. 26, Stage 2). Seaward of this, preglacial marine muds in the inner floating-shelf ice zone were covered by a veneer of till sediments. These were in part redeposited by ocean-bottom currents producing thin beds of sand and clay separating massive diamictite (Fig. 7). Sediments of outer zones are not represented in present Toby exposures.

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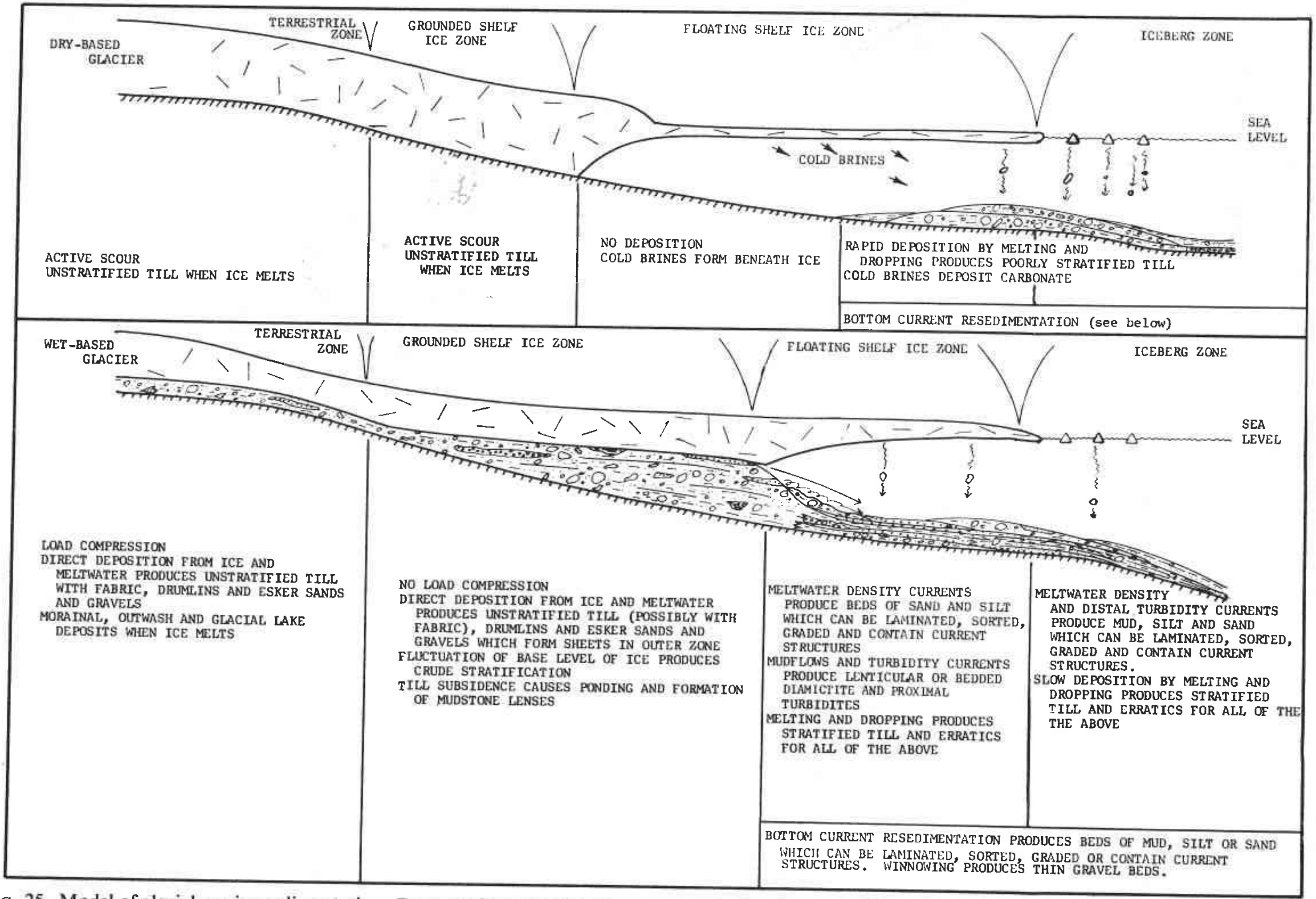

FIG. 25. Model of glacial marine sedimentation. Cross-sections of wet- and dry-based glaciers in a coastal situation with a listing of various distinct depositional zones and processes. Each zone may be hundreds of kilometers wide. Wet-based glaciers are those with melting basal ice. Dry-based glaciers are those with basal temperatures below the local ice melting point. Adapted from Carey and Ahmad (1961) and Reading and Walker (1966).

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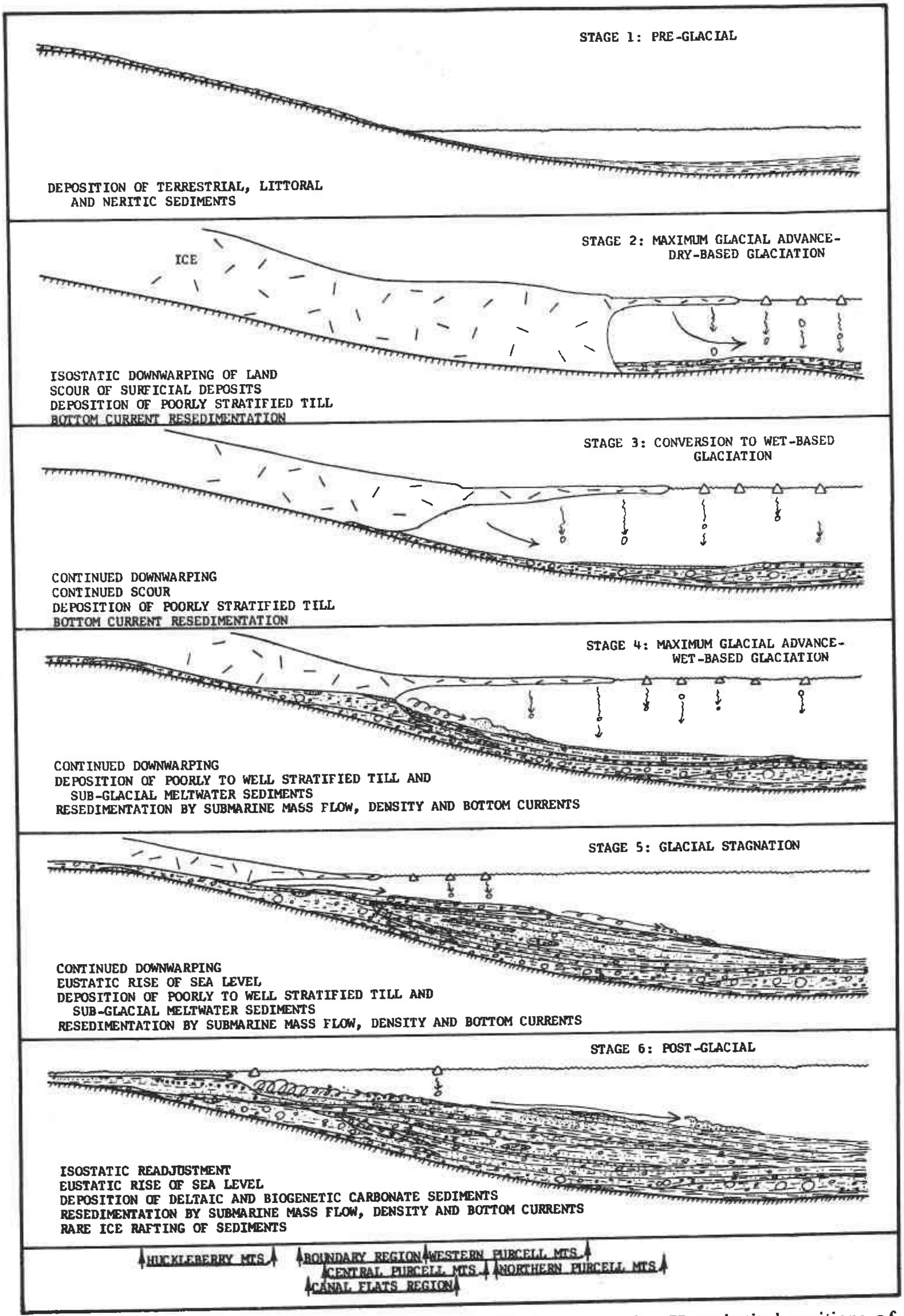

FIG. 26. Inferred depositional history of the basal Windermere series. Hypothetical positions of present areas of Toby exposure are indicated by arrows at bottom. Stages 1 and 2 portray conditions prior to most Toby deposition. Stages 3–5 portray conditions during most Toby deposition. Stage 6 portrays conditions during the deposition of the basal Horsethief Creek Group and Monk Formation.

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Ice stagnation and basal melting are thought to have initiated a conversion to wet-based glaciation, and the rapid deposition of poorly-stratified till in most regions of Toby exposure (Fig. 26, Stage 3). Thick till (the present basal Toby diamictite) blanketed either an unweathered Upper Purcell bedrock surface, local thin zones of mixed ice-transported and plucked debris, or the resedimented tills of the earlier dry-based ice advance (Figs. 18, 19). Bottom currents active during and after periods of melting and dropping produced thin lenses and interbeds of laminated or massive mudstone, sandstone (which might be graded or rippled), and sandy conglomerate (Figs. 6–8). Current effects and daily or seasonal variations in melting imparted crude stratification to the till.

Further basal melting, perhaps combined with advance of wet-based glaciers over a tectonically and isostatically subsiding Montania initiated deposition in all Toby areas (Figs. 24, 26, Stage 4). The combined effects of uneven ice advance and uneven rates of downwarping contributed to lateral thickness variations among accumulating debris. Wasting of grounded shelf ice produced crudely stratified till and associated subglacial lenses of esker sands and gravel among masses of till (Fig. 16). Eskers merged seaward and produced sheet sands and gravels as well as gravel detritus deltas marginal to the floating shelf-ice zone. Subglacial ponding of meltwater in irregularities of the subglacial till sheet produced lenses of mudstone or fine sandstone within the till (Fig. 7). Within the floating shelf-ice zone, the combined effects of density flows, bottom currents, and ice rafting produced the complex association of lithologies most characteristic of the middle part of the Toby Conglomerate. Slumping of till and esker deltas marginal to this zone produced lenticular or bedded mudflow, proximal turbidite, and sandflow deposits (Figs. 6–8). Suspended sediment density currents of meltwater outwash produced massive mudstone beds. If pulsating, they produced laminated mudstone with fine current structures. Periodic ice rafting provided erratics for all lithologies. Bottom–current resedimentation caused the formation of bedded clastics with all degrees of grain size, sorting, fabric, and current features. Advances and retreats of the ice produced interstratification of these and grounded shelf-ice deposits. In the iceberg zone, deposition from slow melting and dropping, from distal turbidity currents, from meltwater density currents, and from bottom–current resedimentation produced thin-bedded mudstones, fine graded, laminated or massive sandstones, a few beds of stratified till, and dropstones for all of these sediments.

As ice stagnated and retreated and sea level rose, sediments characteristic of the outer zones were deposited over those of inner zones (Figs. 18, 19). Toby deposition was largely characterized by iceberg rafting, submarine mudflows, turbidity currents, meltwater density currents, and bottom–current resedimentation (Fig. 26, Stage 5). At this time submarine volcanism occurred in the Huckleberry Mountains and Boundary Region, producing closely-associated till and volcanics. Initially these were intermixed and formed slurries, which produced lenses and beds of volcanic conglomerate and thin beds of tuff and flow-rock among the tills. As volcanism progressed little till was deposited and flow-rock, breccias, and agglomerates were formed in considerable thicknesses over large areas. In the Boundary Region, a post-volcanic continuance of either direct glacial deposition or mudflow resedimentation of till is evidenced by the presence of thick diamictites lacking abundant volcanic clasts (Fig. 19).

As ice retreated from the region of Toby deposition and sea level rose, Horsethief Creek strata were deposited (Fig. 26, Stage 6). Rivers carried vast amounts of detritus westward from the stagnating ice sheet and built large deltas at the cratonic margin. Slumping of deltaic and older till deposits caused by overloading or tectonic shock produced uncommon submarine mudflow and abundant turbidity current and grain flow deposits. The latter were derived by resedimentation of moderately-to-well - sorted deltaic coarse sand and gravel. This produced graded to ungraded thick beds of gritty sandstone, pebbly coarse sandstone, and quartz–pebble conglomerate (Figs. 20, 21). Beds contained mudstone ripups but no traction–current features and were interstratified with mudstones and turbidites (Aalto and Dott 1970; Stauffer 1967). Finely laminated mudstones probably were produced when rivers carried quantities of rock flour to the sea, particularly during warmer seasons. Clouds of muddy suspended sediment traveled in pulsating density currents downslope to the low-energy, pro-delta environment. Set-

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tling and sorting by weak bottom currents produced alternating silt and clay deposition (Fig. 23; Lombard 1963). Ocean – bottom – current resedimentation produced bedded muds, sands, and gravels with all degrees of sorting. These contained a variety of primary structures, including cross beds, ripples, and parallel lamination. Rafting from rare icebergs transported down rivers produced erratics among all lithologies. Massive lenticular dolomite masses apparently were formed in place, as evidenced by their lateral facies relationships with surrounding coarse clastics, perfect concordance with surrounding beds and lack of underlying slump or slide features. They were probably produced during periods of little density-flow by deep water algae that managed to gain a foothold on gravelly, well-washed portions of the seafloor (Wilson 1969, p. 10).

The Late Precambrian Ice Age

Diamictite deposits similar in age to the Toby Conglomerate have been described at several localities in every continent by the Antarctic (Schwarzbach 1963, pp. 118–120). Such deposits in North America have been described by Blackwelder (1926), Condie (1967), Gabrielse (1967), and Ziegler (1959). This suggests that at this time environments conducive to the formation of diamictite were widespread. Most such deposits are not unequivocally glacially-induced. The lack of compelling proof of glaciation has brought workers to stress the possibility of their emplacement by non-glacial mass flow (Condie 1967; Schermerhorn and Stanton 1963). The presence of most such deposits within stratigraphic sequences reflecting tectonic instability has been related to the likelihood of emplacement by mass flow triggered by shock. However, it is equally true that Late Precambrian sediments would be most readily preserved in rapidly subsiding areas characterized by rapid sediment accumulation. In most cases the possibility of glacial marine sedimentation associated with mass flow cannot be excluded.

Skepticism stems from the paleomagnetically-deduced low-latitude position of most Upper Proterozoic diamictites, including the Toby Conglomerate (Harland 1964). But some low-latitude deposits have survived the closest scrutiny and remain confirmed tillites (Crowell 1964, p. 95; Harland 1965; Reading and Walker 1966; Spencer 1968). Their existence lends credence to the glacial association of diamictites of similar age the world over. If many are in fact glacial, they provide an excellent marker for worldwide Proterozoic correlation.

Continental glaciation in equatorial regions has an aura of catastrophism. The several factors that are suggested to enter into initiation of a glacial epoch may all have been operative. These are: cyclical fluctuations of solar radiation, cyclical astronomic variations between the earth and sun, and epeirogeny (Emiliani and Geiss 1957). The latter in turn affects strongly the distribution of land and thus ocean current systems, an increase of atmospheric carbon dioxide, introduction of quantities of volcanic ash and soot into the stratosphere, and increased albedo of the earth's surface (Schwarzbach 1963). During the Proterozoic, albedo, and atmospheric dust content could have been enhanced by the lack of terrestrial plant cover. Even so, Harland (1964) speculates that these factors would not be sufficient to produce an ice age of the required magnitude. Instead, he would invoke a truly non-uniformitarian change, perhaps in the amount of solar radiation.

An extensive Late Precambrian ice age attractively explains several classic problems. Widespread peneplanation and subsequent Cambrian transgression could in part be produced by glacial scour and postglacial eustatic rise in sea level. Rudwick (1964) even suggested that the explosive evolution of neritic and littoral Cambrian fauna might have been initiated by the shift from adverse climate and few shallow seas to milder climate and widespread epeiric transgression, perhaps allied with a decrease in lethal solar radiation. Thus a Late Precambrian worldwide ice age is an attractive hypothesis, that is further complemented by the study of the Toby Conglomerate. Physical processes in nature are operatively uniform but we must view them as actualists. We must recognize their true evolutionary perspective, and realize that non-uniformitarian shifts in magnitude or coordination of these processes may have effected the earth in the past. A phenomenon as vast as this early ice age must be appreciated in our reconstruction of earth history.

Conclusions

The Toby Conglomerate consists of approximately 65% massive diamictite, 20% argillite, and 15% conglomerate and sandstone. Argillite and

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sandstone isolated megaclasts. Clasts constitute an average of 18% of the rock. For all regions, Toby diamictite clasts consist of an average of 61% quartzite, 26% carbonate, 11% argillite – slate – phyllite, 1% sandstone and traces of conglomerate, chert, vein quartz, and plutonic, gneissic and vocanic rock. Clasts are supported in a sandy argillite matrix composed of 44% sand and 56% quartz silt, micrite, and/or clay. Regional compositional and textural variations are slight, reflecting a general homogeneous heterogeneity throughout the Toby Conglomerate.

The Toby Conglomerate varies markedly in thickness, by as much as 1800 m in less than 10 km. There is little orderly vertical or lateral stratigraphic variation. However, basal beds are predominantly diamictite while upper parts of sections more commonly contain argillites and fine sandstones. In Washington and in the boundary region of Washington, Idaho, and British Columbia, Toby diamictite is conformably overlain by and partially interstratified with extrusive volcanic rock containing pillow lavas. Elsewhere, the Toby Conglomerate is overlain by argillites, slates, sandstones, and conglomerates of the Horsethief Creek Group.

The Toby Conglomerate and basal Horsethief Creek Group were most likely produced largely by glacial marine sedimentation. First, dry-based continental glaciers encroached over Montania, a low relief landmass produced by the East Kootenay orogeny. Second, these converted to wet-based glaciers and deposited subglacial tills and associated density-flow sediments with accompanying submarine volcanism. Third, submarine deposits resulted from submarine mass flow associated with the slumping of outbuilding deltaic and older till deposits, and from rivers rich in rock flour entering the sea.

The Toby Conglomerate of British Columbia is correlative with the Huckleberry Conglomerate and Volcanics of Washington. The boundary between the Toby Conglomerate and Horsethief Creek Group as placed above predominant diamictite in the Purcell Mountains probably is an approximate time datum reflecting the cessation of ice wasting as a dominant agent of deposition. If consistency were to be maintained throughout all Windermere exposures, this boundary would be shifted above the diamictite-rich zone overlying the Irene and Leola Volcanics in British Columbian and Washington, thus making them members of the Toby Conglomerate.

The presence of granitic clasts most probably derived from the Archean Canadian shield in many areas of Toby exposures suggests that Montania had low enough relief to permit its overriding by continental glaciers, although local highs may have served as minor centers of ice spreading. Thus East Kootenay orogenesis must have been comparatively mild, accompanied by broad slow uplift of land, mild folding, and extrusive volcanism. Uncommon plutons of Late Purcell age, and evidences of differential erosion prior to the beginning of the Cambrian Period suggest moderate tectonism in select regions. Tectonic activity continued through Windermere times, causing local crustal downwarping which, combined with submergence of an undulating land surface and uneven advance of glacial ice, helps to explain the considerable lateral thickness variations of the Toby Conglomerate.

Acknowledgments

Funding for this doctoral study was provided by grants from the Geological Society of America, the Society of the Sigma Xi, the Humble Oil and Refining Company, and the National Aeronautics and Space Administration. I wish to extend thanks to my thesis advisor, R. H. Dott, Jr., who suggested the project and provided considerable advice and direction contributing to its success. Also to R. L. Muller, who assisted in fieldwork, and D. L. Clark and L. C. Pray, who provided useful criticism of the dissertation. Lastly to my wife, Frederica, for assistance in fieldwork. Copies of the dissertation resulting from this study are filed at the University of Wisconsin Memorial Library and the University of Wisconsin Geology Department library (catalog number UW 1533). A collection of reference specimens is maintained by the University of Wisconsin Geology Department under catalog number UW 1533.

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