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TUBER AND STARCH CHARACTERISTICS OF ALBERTA GROWN NETTED GEM POTATOES

by

© IVY S. O. CHUNG

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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OF

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled

"TUBER AND STARCH CHARACTERISTICS OF ALBERTA GROWN NETTED GEM POTATOES"

submitted by IVY S. O. CHUNG in partial fulfilment of the requirements for the degree of Master of Science.

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Supervisor

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.....May 24, 1979.....

Date

ABSTRACT

Starches isolated from three graded sizes of Netted Gem potatoes grown commercially in Southern (Vauxhall), Central (Winterburn), and Northern (Peace River) Alberta were studied for physicochemical properties such as mineral composition, amylose content, and swelling and solubilization patterns. Also determined were dry matter and starch contents, mineral composition, and anatomical characteristics of the tubers, grain size distribution within the tubers, and their suitability for French fry processing as judged by oil uptake. Statistical analyses indicated the highly significant role of location of growth in influencing some tuber and starch properties. Tuber dry matter and starch contents were significantly higher for Vauxhall potatoes in comparison to those from Winterburn or Peace River. In addition, Vauxhall potatoes exhibited significantly lower oil uptake relative to the other locations. There was no interdependence between growth location and tissue cell size or starch grain distribution. Starches from Vauxhall and Winterburn grown tubers had significantly higher iodine binding capacity and amylose contents than those from the Peace River region. Scanning electron micrographs were used to illustrate the behavior of potato starch grains during gelatinization, and the findings were correlated with current concepts of starch grain ultrastructure.

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1.0 INTRODUCTION

Currently, 35% of the potatoes produced in Alberta are consumed as fresh table potatoes, 5% are used for seed production, and 60% are processed into dehydrated granules, chips, or French fries.

Most processors in Alberta favor the Southern grown potatoes over those grown in Central and Northern regions, claiming that Southern potatoes have better "processing quality". In response to the concern of all growers, research was initiated to investigate some of the parameters influencing processing quality. Starch was isolated from tubers and analyzed for its physicochemical characteristics in relation to growth location and tuber size. In addition, comparisons were made for average tissue cell size and starch grain distribution in whole tubers. The oil uptake by French fries was compared for the various tuber categories, and discussed in relation to the parameters investigated. All these results, aside from providing useful data to processors of French fries, will be of academic value and interest by serving as a source of information on tuber and starch characteristics of Alberta potatoes.

II. LITERATURE REVIEW

A. Potato production in Canada and Alberta

1. Seeded area, yield, and production

The production of potatoes in both Canada and Alberta has been fairly stable over the past decade (Table 1). In spite of the reduction in seeded area devoted to the potato crop in Alberta since 1978, production has remained rather constant owing to improved yields. At present, Alberta ranks second among the Western Provinces, accounting for approximately 8% of the country's total production (Table 2).

In Alberta, about 80% of the crop is grown in the Southern regions, with Netted Gem being the most common commercially grown cultivar. About 60% of the crop is processed into dehydrated granules, chips, and French fries. In addition, some is canned, or utilized for starch production.

2. Some cultural practices in potato cultivation in Alberta

A summary of the available information is presented in Table 3. Seeding and harvest take place at about the same time in Southern, Central, and Northern Alberta. In Southern Alberta, however, the crop is usually planted with closer spacing, and a considerably lower rate of fertilizer application is used when compared to the Central and Northern locations. Irrigation, though not required in the latter two areas, is a must in the South in order to

Table 1. Seeded area, average yield, and production of potatoes in Alberta and Canada (1971-1978)*

Crop year	Alberta			Canada		
	Area (ha)	Yield (kg/ha)	Production (t)	Area (ha)	Yield (kg/ha)	Production (t)
1971	10,562	17,179	181,440	108,700	20,368	2,214,000
1972	9,308	19,980	185,976	98,800	20,148	1,990,600
1973	9,308	21,930	204,120	105,500	20,460	2,158,500
1974	9,308	19,493	181,440	114,400	21,721	2,484,900
1975	7,284	21,173	154,224	105,300	20,845	2,195,000
1976	6,556	24,908	163,296	114,800	23,005	2,641,000
1977	6,880	24,394	167,832	111,500	22,310	2,487,600
1978	6,880	25,053	172,368	111,600	19,722	2,201,000

*Statistics Canada.

Table 2. Seeded area, average yield, and production of potatoes in Canada in 1977 and 1978.*

Province	Area, ha		Yield, kg/ha		Production, t	
	1977	1978	1977	1978	1977	1978
Prince Edward Island	22,258	22,663	24,278	20,645	540,374	467,888
Nova Scotia	1,538	1,538	18,374	18,433	28,259	28,350
New Brunswick	23,067	23,472	21,814	19,727	503,178	463,035
Quebec	18,211	18,616	20,006	18,830	364,332	350,542
Ontario	19,466	17,887	25,073	18,477	488,074	330,493
Manitoba	14,974	15,783	16,661	17,819	249,480	281,232
Saskatchewan	688	728	27,690	22,431	19,051	16,330
Alberta	6,880	6,880	24,394	25,053	167,832	172,368
British Columbia	4,452	4,047	28,528	22,417	127,008	90,720
Total	111,534	111,614	22,303	19,719	2,487,588	2,200,958

*Statistics Canada.

Table 3. Some cultural practices employed in the cultivation of potato crops in Alberta.

Location in Alberta	Time of seeding	Time of harvest	Plant spacing (cm)	Fertilizer applied (kg/ha) N*	P_2O_5	K_2O	Irrigation**
South	April 21-May 31	Sept. 5-Oct. 15	30	40	45	68	+
Central	April 21-May 31	Sept. 15-Oct. 15	36	110-170	110-170	335	-
North	May 1-May 25	Sept. 15-Oct. 15	36	110	85	450	-

*Urea or ammonium nitrate or sulfate.

**Sufficient water was applied to maintain soil moisture at above 50% field capacity.

maintain soil moisture at a level above 50% of the field capacity.

B. Factors influencing the processing quality of potatoes in relation to French fry production

The processing quality of potatoes can vary not only among tubers, but also within a tuber. Climate, and cultural and storage practices contribute to the variability.

Therefore, selection of raw material has been accorded careful attention by processors, the acceptability of tubers being dictated by the type of end product desired, and by processing conditions. Specific gravity and dry matter (DM) content have always been utilized as practical criteria in the assessment of processing quality of tubers. While positive correlations with tuber processing quality have been established with these two factors (Barrios et al., 1961a), contradictory findings have also been reported (Kunkel and Holstad, 1972; Motes and Greig, 1970). However, as pointed out by Weaver et al. (1975), specific gravity measurements, in conjunction with determination of reducing sugar content and frying tests, still provide the best basis for screening of raw tubers for frying.

The quality attributes of major concern to processors are color, flavor, and texture of French fries (Maclean et al., 1966). Factors known to influence French fry quality include the cultivar of potato, and cultural and environmental, storage, and processing conditions.

1. Potato cultivar

The potato cultivar is widely accepted to exert the greatest influence on processing quality. Using cultivars of high DM content (high specific gravity) would usually ensure a satisfactory end product characterized by increased yield, crispness, and mealiness, low oil content, and improved flavor (Maclean et al., 1966; Kirkpatrick et al., 1956).

Cultivars also vary in reducing sugar content (Swiniarski and Ladenberger, 1970), tendency to accumulate reducing sugars during storage (Agle and Woodbury, 1968; Samotus et al., 1974a,b; Miller et al., 1975), and response to conditioning (Agle and Woodbury, 1968; Iritani and Weller, 1977) -- all of which have a role to play in determining the appearance (color) of the end product.

Mohr (1972) reported that the amount of pith tissue in the tuber was cultivar dependent. Pith tissue, which is lower in starch content than cortex or perimedullary tissue, exhibits a greater tendency to absorb fat during frying than perimedullary tissue, thus adversely affecting the textural quality of the fried product.

2. Cultural and environmental conditions

Cultural and environmental conditions include: time of planting and harvest, plant spacing, soil type, temperature during the growing season, available moisture, fertilization, insect and disease control, and vine killing.

The time of planting and harvest, along with a

multitude of other factors such as insect and disease control and vine killing, affects the maturity of tubers, which then affects the quality of the processed product (Smith, 1975a).

Decreased plant spacing (i.e., increased plant population) was found by Bleasdale and Thompson (1968) to result in potatoes high in specific gravity and DM content. This might have been a result of decreased soil fertility and water availability, factors which correlate with increases in specific gravity and DM content (Smith, 1975c). These findings, however, were not substantiated by Tims et al. (1963), who indicated that seed spacing had no appreciable effect on specific gravity of the 'White Rose' cultivar in three out of four trials.

Soil type exerts its influence on quality via differences in water holding capacity, drainage, aeration, temperature, or fertility. Nash (1941) stated that soil type has little or no influence on DM content, and Neenan et al. (1967), in an investigation involving mineral and peat soils, concluded that soil type has little, if any, influence on specific gravity of potatoes.

The rates of metabolic activities of the potato plant, such as uptake of nutrients, photosynthesis, and respiration, are largely influenced by temperature during growth (Smith, 1975a). The author stated that reduced accumulation of carbohydrate reserve in tubers occurs at high temperatures, since the increase in the rate of

respiration is greater than that of the rate of photosynthesis, thus resulting in low specific gravity tubers. The observations of Notes and Greig (1969, 1970) lend support to this statement. They noted the associations between high air and soil temperatures, and low specific gravities and dark chips or fries. This can be avoided by irrigation, which serves to lower the soil temperature, thereby minimizing the loss of carbohydrate reserve through respiration (Notes and Greig, 1970). However, it is generally conceded that excessive application of water, particularly during a low temperature growing season, often results in reduced DM content and specific gravity of potatoes (Prince and Blood, 1962).

Results reported in the literature are not unanimous regarding the effect of fertilizers on quality, but, in general, increased fertilizer application decreases specific gravity (Kunkel and Holstad, 1972). Of the three major mineral nutrients, N and K are considered to bear more significance than P in affecting specific gravity (Lujan and Smith, 1964).

Maclean et al. (1966) found that French fry quality characteristics were lowered by increased N application, whereas P fertilization had no effect. With increased K fertilization, improvements in only some of the quality attributes were observed.

The form of fertilizer (Lujan and Smith, 1964; Maclean et al., 1966) and the method of fertilizer placement (Smith,

1975a) has also been implicated in influencing processing quality.

3. Storage conditions

The significance of storage conditions in relation to processing quality of potatoes is well established (Hyde and Morrison, 1964; Cunningham et al., 1966; Schippers, 1971; Samotus et al., 1974a; Iritani and Weller, 1977). Ideally, storage conditions should permit rapid wound healing of the tubers immediately after harvest, with minimum sprout growth and loss in weight, no decrease in specific gravity, and little or no accumulation of reducing sugars. It is generally recommended that potatoes which are to be processed into French fries be stored at 10-12.8°C (Smith, 1975b). Sparks (1973) found lower peel and trim losses, as well as lower sugar content of tubers, lighter color, and better flavor and texture (mealiness and crispness) of French fries processed from tubers ventilated with air of at least 95% relative humidity. On the other hand, Smith (1975b) stated that storage at about 4.4°C to avoid infection and decay of tubers is advisable if field frost or late blight rot is in evidence. The author also pointed out that tubers stored at temperatures below 10°C must be reconditioned at a temperature between 15.6 and 26.7°C, while maintaining relative humidity between 75 and 80%, until a desirable level of reducing sugar is attained, as revealed by frying tests.

4. Processing conditions

The effects of processing on French fry quality were reviewed by Weaver et al. (1975). Processing methods or conditions in the French fry industry are often monitored to ensure that the end product will be of optimum quality. For instance, hot water blanching of French fry strips prior to frying results in a more uniform color, reduced oil content, and improved texture of the final product (Isleib et al., 1964; Weaver et al., 1975).

In addition to blanching, the oil content of the fried product can be controlled by manipulating thickness of slices, and frying conditions. Hydrogenated vegetable oil, because of its improved stability against rancidification, is used rather extensively as a frying medium. Frying temperature is of importance. In general, a rise in temperature increases oil deterioration, leading to French fries of inferior quality due to off-flavor development. However, oxidative stability of the frying oil at elevated temperatures can be achieved by the addition of silicone oil (organo polysiloxanes), which also serves to increase the smoke point of the frying oil and, in so doing, minimizes charring of French fries, thereby reducing off-flavor development in the end product (Babayan, 1961).

C. Starch biosynthesis

It is widely accepted that the biosynthesis of starch is initiated inside the cytoplasmic organelles known as plastids (Badenhuizen and Chandorkar, 1965). Although much

is known about enzymic reactions during starch synthesis, the mechanisms involved in starch grain formation are not well established, as is apparent from a number of reviews (Pazur, 1965; Manners, 1968; Badenhuizen, 1969; Marshall, 1972; Banks and Greenwood, 1975).

The principal enzymes which have been associated with starch biosynthesis are: (a) phosphorylase (α-1,4-glucan:orthophosphate glucosyl transferase, E.C.2.4.1.1), also known as P-enzyme; (b) Q-enzyme (α-1,4-glucan:α-1,4-glucan 6-glycosyl transferase, E.C.2.4.1.18), a branching enzyme; and (c) starch synthetase [uridine or adenosine diphosphate glucose (UDPG, ADPG):α-1,4-glucan 4-glucosyl transferase, E.C.2.4.1.21].

In vitro, phosphorylase, with malto-oligosaccharides as primers, produces amylose from glucose-1-phosphate (G-1-P), while Q-enzyme produces amylopectin from amylose. A chain length of at least 40 glucose units is required for potato Q-enzyme action (Nussenbaum and Hassid, 1952). Starch synthetase, on the other hand, using UDPG or, preferably, ADPG as a glucosyl donor, is capable of synthesizing α-1,4 bonds (Frydman, 1963). This enzyme, because of its strong adsorption to the starch grain, has been reported by Chandorkar and Badenhuizen (1967) to be an integral part of the starch grain structure. A soluble starch synthetase capable of utilizing only ADPG as a glucosyl donor has also been isolated from potato tubers (Frydman and Cardini, 1966).

Doubts have been expressed concerning the role of phosphorylase as the major starch-synthesizing enzyme upon the discovery of starch synthetase, an enzyme which [redacted] sugar nucleotides as glucose donors (Leloir et al., [redacted]). In spite of this, there are still claims that phosphorylase is responsible for a large portion of starch synthesis (Teal and Nelson, 1969; Badenhuizen, 1963, 1969). As Badenhuizen (1969) indicated, no satisfactory evidence exists which would disqualify phosphorylase as the principal enzyme in starch biosynthesis.

ADPG-starch synthetase, the presence of which has been reported in amylose-containing starch grains (Fekete et al., 1960), has not been proved to be the major starch synthesizing enzyme (Badenhuizen, 1969, 1973). However, it is assumed that the enzyme may serve the important function of producing oligosaccharides from maltose, which could then serve as primers for phosphorylase. Badenhuizen and Chandorkar (1965) also postulated that the presence of linear molecules in grains may be attributed to the strong affinity of the enzyme for starch molecules.

The relative importance of phosphorylase and starch synthetase in *in vivo* starch formation is still uncertain, but, as stated by Banks and Greenwood (1975), the fact that both enzymes are present in adequate amounts in the starch-synthesizing tissues of higher plants makes it possible that all the α-1,4 linkages synthesized can be attributed to either enzyme. However, the prominent role

assumed by phosphorylase over starch synthetase in starch biosynthesis has been implicated in potatoes (Pottinger, 1964).

The realization that the P- and Q-enzymes are both soluble and localized in the plastidal stroma (Badenhuizen and Chanderbar, 1965) poses a fundamental problem in the understanding of the mechanism of starch biosynthesis. It is difficult to account for the coexistence of linear and branched molecules within the starch grain.

Several theories have been advanced to explain this phenomenon. The compartmentalization theory of Whelan (1958) suggests that the synthesis of linear and branched molecules takes place in two compartments, separated by a membrane which prevents free diffusion of the enzymes. The membrane is, however, permeable to glucose and oligosaccharides of low degree of polymerization (DP). A schematic representation of this theory is given in Figure 1.

According to this theory, D-enzyme brings about a disproportionation of the maltotetraose (primer), causing three glucose units of the primer to be incorporated into amylopectin and one into amylose, thereby accounting for the commonly encountered 3:1 ratio of amylopectin to amylose in most natural starches. The theory was subsequently revised to accomodate the role played by starch synthetase (Whelan, 1963). The modified scheme (Figure 2) shows the formation of amylose from ADPG or UDPG by starch synthetase, while the

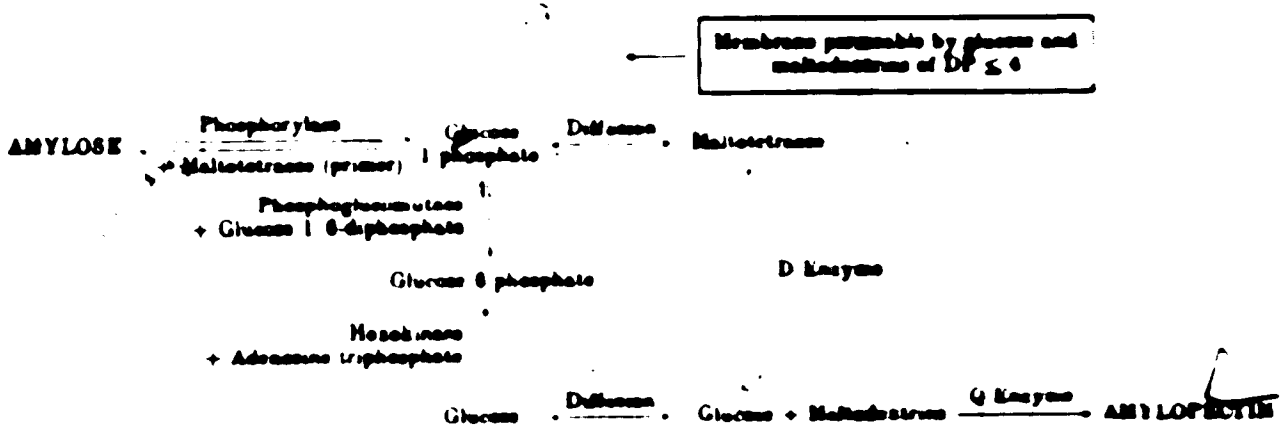

Figure 1. Illustration of the synthesis of amylose and amylopectin from maltotetraose (Whelan, 1958).

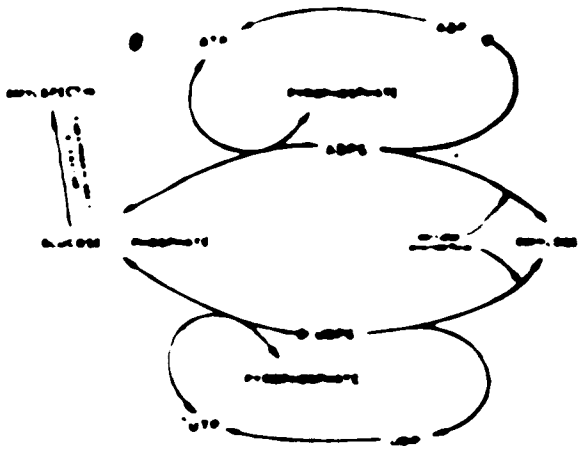

Figure 2. Scheme representing the synthesis of amylose and amylopectin from nucleoside diphosphate sugars (Whelan, 1963).

synthesis of amylopectin is carried out by phosphorylase and D-enzyme in the presence of G-1-P and primer.

The amylopectin in this scheme plays the role of a physical barrier. It surrounds the amylose-synthesizing enzyme, thus preventing the diffusion of D-enzyme to the site of amylose synthesis. However, the barrier does allow the passage of the ADPG or UDPG molecules, which are glucosyl donors in amylose synthesis.

Starch synthesis involving a glycogen precursor mechanism was favored by Erlander (1958). The proposed mechanism involves the conversion of glycogen (also known as phytoglycogen) to amylose and amylopectin via the action of a debranching enzyme. The linear chains obtained by the removal of the exterior α-1,6 linked chains are believed to be joined together to form amylose, while the residual debranched glycogen constitutes the amylopectin. This postulate has received little support since glycogen has not been found in any plant other than sweet corn, and there is no evidence for the presence of a debranching enzyme in plants which will act on glycogen (Marshall, 1972).

Geddes and Greenwood (1969) have suggested a multi-pathway system for starch biosynthesis (Figure 3). An outstanding feature of the postulate relates to the formation of a linear dextrin 'pool' derived from transglucosylase pathways, phosphorylase synthesis, or amylose degradation. Also, the growth of the grain takes place by apposition at the grain surface. The intense

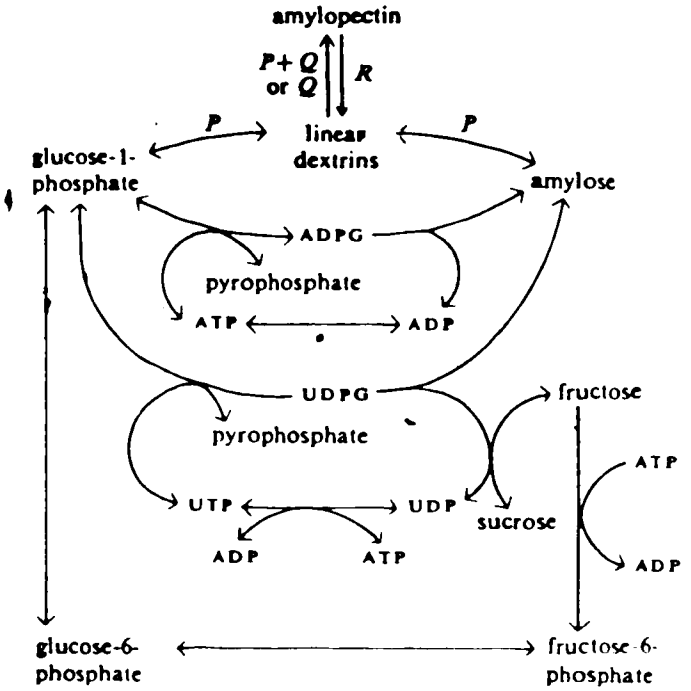

Figure 3. Scheme for starch biosynthesis proposed by Geddes and Greenwood (1969).

synthesis of linear chains at or near the surface saturates the activity of Q-enzyme, thereby preventing a proportion of the molecules from becoming branched. This hypothesis explains the observed increase in amylose content (relative to amylopectin) with increase in grain size.

A concept in favor of the amylose-precursor mechanism was proposed by Badenhuizen (1963). The author also favored the view that grain formation progresses by rapid periodic crystallization of a coacervate within the matrix of the amyloplast. In each coacervate droplet, linear molecules, which are continuously formed, are gradually branched by the Q-enzyme. Crystallization may occur before branching is complete (ordinary starches), or after it has been completed (waxy starches). Deposition of the coacervate droplets takes place at the periphery of the already existing starch grain.

Evidence in support of growth by apposition was provided by Badenhuizen and Dutton (1956) by using a C^{14}-labelled precursor and following the growth of the starch grain. Badenhuizen's theory suggests an even distribution of the linear and branched components within the grain of ordinary starches, an assumption which is not inconsistent with the observation that residual potato starch grains obtained after bacterial α-amylase treatment contain the same amount of amylose as was in the original grain (Leach and Schoch, 1961). Intussusception, according to Badenhuizen (1965), is responsible for the lengthening of

the existing molecules, particularly the linear chains. This provides an explanation for the apparent increase in the linear component during starch grain growth. A proposed pathway for the biosynthesis of starch components is given in Figure 4 (Badenhuizen, 1969).

Some distinctive features of the scheme (Figure 5) in relation to the biosynthesis of starch components, advanced by Marshall (1972), point to the assumptions that: (a) ADPG is the precursor of amylopectin, and UDPG of amylose; and (b) phosphorylase plays a minor role, if any, in starch synthesis. Nevertheless, the absence of pyrophosphorylase in potato tubers implies that ADPG may be generated via another route, probably that which involves sucrose synthetase (Cardini and Recondo, 1962).

A recent contribution to knowledge of starch biosynthesis, made by Schiefer et al. (1973), bears some resemblance to Marshall's proposed scheme. They also established the formation of amylopectin by a synthetase-branching enzyme complex and that of amylose by a synthetase, the ratio of amylose/amylopectin being determined by the ratio of the two forms of synthetase enzymes.

The foregoing reviews show that the mechanism of starch biosynthesis has not yet been fully elucidated, thus emphasizing the need for further research in this area.

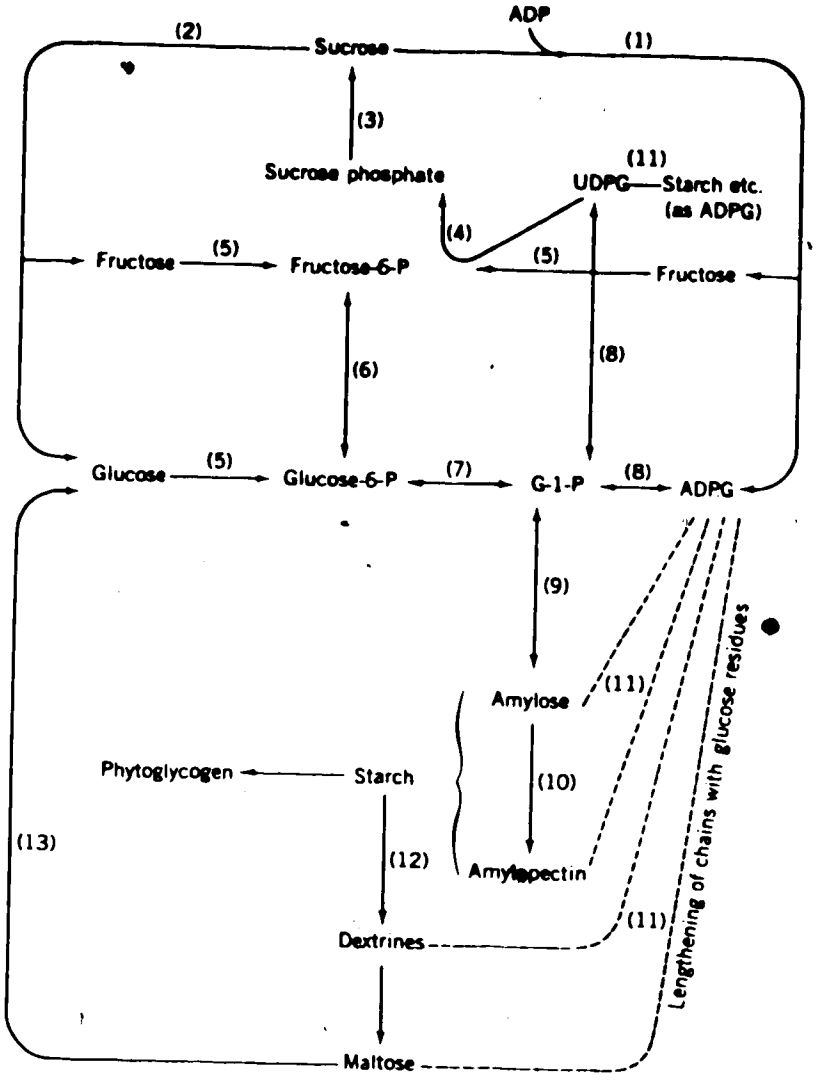

Figure 4. Schematic representation for starch formation proposed by Badenhuizen (1969). The enzymes involved are: (1) ADPG-fructose glucosyl transferase, (2) invertase, (3) sucrose phosphatase, (4) UDPG-fructose phosphate glucosyl transferase, (5) hexokinase, (6) isomerase, (7) glucomutase, (8) pyrophosphorylase, (9) phosphorylase, (10) Q-enzyme, (11) α-glucan glucosyl transferase, (12) amylases, (13) maltase.

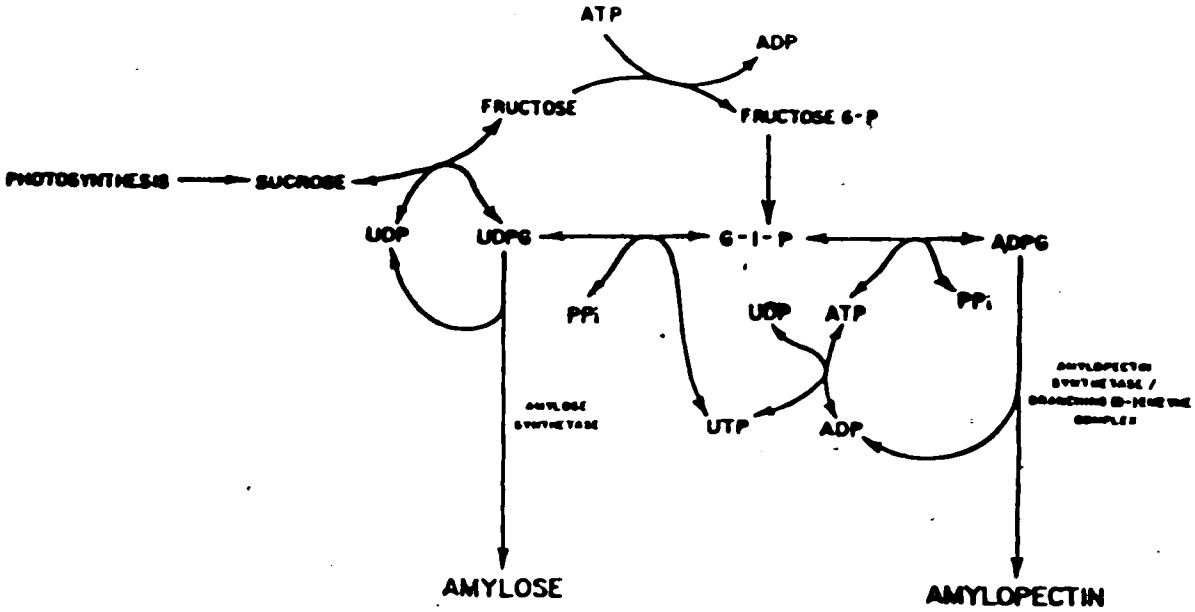

Figure 5. Scheme for the biosynthesis of starch components (Marshall, 1972).

D. Some properties of potato starch

1. Fine structure of the starch grain

Starch grain structure varies with the starch source, so knowledge acquired from the study of a given starch should not and cannot be extended to starch grains in general. Emphasis in this discussion will be on literature pertinent to potato starch structure. Since the subject has been critically reviewed by Sterling (1968), and, more recently, by Banks and Greenwood (1975), attention will be given largely to literature published within the past decade.

Native starches are semi-crystalline, and, depending on their crystallinity patterns, as revealed by X-ray diffraction spectra, can be arbitrarily classified as A-, B-, and C-starches. Most cereal starches are A-starches, while potato and amylomaize are representative B-starches. C-starches, which include those from smooth peas and beans (Katz and van Itallie, 1930), exhibit an X-ray diffraction pattern intermediate between those of A- and B-starches. It is of interest to note that the crystallinity of potato starch, estimated at 22% (Sterling, 1960), has been attributed to the amylopectin component, while amylose would be in the amorphous state (Banks and Greenwood, 1975).

The starch grain, which is birefringent (a phenomenon indicative of a high degree of molecular order and orientation), also has lamellations in its structure -- a feature accentuated by acid or enzyme treatments (Hollinger

and Marchessault, 1975). The development of these shell structures is believed to be influenced by environment. While such a concept holds true for wheat grains, shell formation in potato grains is independent of the effects of day-night alternation (Buttrose, 1962). Rather, endogenous rhythm, which regulates the supply of starch precursors and, thus, molecular packing density, is responsible for the control of shell formation in potato starch grains.

The layering effect is an important part of some starch grain models. A proposal for a lamellar model for Shoti starch, in accord with the long-held view of appositional growth of starch grains, has evolved as a result of the anisotropic light scattering study conducted by Mencik et al. (1971). Furthermore, a radial arrangement in the grain structure was advocated for the six-fold helices of the starch molecule.

Employing the same technique, Finkelstein and Sarko (1972a,b) concluded that the grain structure of potato starch consists of relatively few but coarse layers (4-7 μm in thickness) with varying degrees of anisotropy. In addition to their suggestion that the coarse layers might be composed of finer sublamellar structures, they also indicated the presence of an isotropic center (hilum) in the grain morphology.

Confirmation of lamellar structures was provided by a scanning electron microscopy (SEM) study of acid and α-amylase treated cross-linked potato starches (Hollinger

and Marchessault, 1975). It was found that the core of the potato starch grain is a region of weak organization, as evidenced by its great susceptibility to the hydrolytic action of acid and enzyme.

On the other hand, in replicas of fracture faces of Lintnerized potato starch, Sterling and Pangborn (1960) could not observe any lamellation, but, instead, provided evidence for the presence of fibrillar organization in the grain structure. They could readily distinguish radially oriented microfibrils (average diameter of about 270 Å, and a length of at least 4000 Å) which seemed to be composed of micellar strands (80-90 Å in diameter), with amorphous starch occupying the intermicellar regions. The microfibrils may join together to form a larger strand. Similar microfibrillar structures were also seen in freeze-etched surfaces of freeze-fractured Lintnerized potato starch grains (Leonard and Sterling, 1972).

Subsequent SEM studies carried out by Sterling (1974, 1976) in the examination of potato starch grains undergoing various stages of gelatinization also suggested deposition of starch molecules in the form of long radial fibrils, of varying diameters (0.1-1.0 μm), radiating from the hilum and traversing the concentric lamellations of the grain structure. It was suggested that these fibrils, asso through hydrogen bonds and/or van der Waals' forces, radially oriented molecules connected by covalent bo the radial direction. Consequently, the regions of

are exclusively radial in the grain structure. Concentric lamellations, believed to be the major organizational factor in the starch grain structure, were also noticeable at the periphery of the starch grain (Sterling, 1974).

The presence of pores on the grain surface is implicated in the fibrillar concept. In native potato starch such pores were found to have diameters ranging form 0.5-75 nm, with small pores (0.5-20 nm) concentrated in the intermolecular and intermicellar spaces within the lamellae, and large pores in the interlamellar regions, the latter representing tangential zones of weakness (Sterling, 1970). The recent findings of Wetzstein and Sterling (1977) and Kassenbeck (1978) also support the fibrillar concept of potato starch grain structure.

By subjecting Lintnerized potato starch to the action of bacterial α-amylase, followed by a mild periodic acid oxidation and silver fixation, Gallant et al. (1972) demonstrated the presence of both radial and tangential (concentric) organization in potato starch grain structure. Radial arrangement of microfibrils was observed in inner regions close to the hilum, while tangential order was evident in the outer regions. These findings confirmed those reported by Sterling (1974).

Another potato starch grain model views the grain structure as consisting of an amylose core surrounded by tangential layers of crystalline isodiametric micelles of folded amylopectin molecules stabilized by intermolecular

hydrogen bonding (Gruber et al., 1973).

An investigation involving tritium-labelled corn and potato starch grains (Nordin et al., 1970) has shed some light on molecular orientation in the grain architecture. The authors suggested that the starch molecules are oriented with their non-reducing end at the grain surface. The implications of this were discussed in relation to the growth of grain structure by apposition.

The chain conformation of starch molecules in starch grains has also been a matter of concern. On the basis of X-ray diffraction studies of oriented B-amylose fibres prepared from potato amylose, Blackwell et al. (1969) suggested that the amylose chain in B-starch is a left-handed, single, six-fold helix. Water molecules, an essential feature of the postulate, are found intercalated between glucose units in adjacent helical turns.

Sarko and Wu (1978), also working with the same specimen, were strongly in favor of a model for A- and B-amylose structure characterized by a right-handed, parallel-stranded, double helix packed in an antiparallel manner. The A- and B-structures, however, differ with respect to the packing arrangement of the helices, and water content.

Another model for B-starch (Kainuma and French, 1972), which involves intertwined double helices, stems from the view that water is not an integral part of B-starch crystal structure. Starch chains, represented by left-handed double

'helices (arranged either parallel or antiparallel), were said to be packed in a way which excludes interchain water.

Worthy of note is the helical carrier chain model for amylopectin developed by Frey-Wyssling (1969). This chain, which can be accomodated in the 0.1 μm apposition lamella, consists of a tangentially oriented six-fold helix carrying radially oriented parallel side chains characterized by three-fold glucosan helices. This gives a grain structure with both lamellar (periodicity = 80 Å) and fibrous (periodicity = 10.6 Å) characteristics. The amylose helical chains, in accordance with the proposed amylopectin ultrastrucutre, assume a six-fold tangentially arranged conformation. Such a helical conformation of the carrier chain in the amylopectin structure was favored by the author over the fold conformation advanced by Mühlethaler (1965) on the grounds that the former was based on the established amylose chain conformation, while regularly folded amylose chains were still of a hypothetical nature. However, the helical model, as Frey-Wyssling (1969) admittec, is not without flaws.

Despite the many investigations that have been conducted, precise information on the structure of native starch grains, with respect to the distribution of crystalline and amorphous areas, and molecular chain conformation, is still lacking, as is obvious from the highly contradictory nature of the viewpoints presented in this review.

3. Starch components

To conduct fundamental investigations on amylose and amylopectin, starch must first be isolated and then fractionated into its two components by non-degradative procedures. Many investigations have been conducted with regard to fractionation techniques (Cowie and Greenwood, 1957a,b; Banks et al., 1969; Gilbert et al., 1964). The most efficient method, as outlined by Banks et al. (1973) and Greenwood (1976), entails pretreatment of starch with dimethylsulfoxide to ensure complete dissolution, dispersion of the grains in water, and selective precipitation of amylose by either thymol or butanol. Purification of the insoluble amylose complex is achieved by recrystallization with butanol. Amylopectin is obtained by freeze-drying the supernatant after removal of the amylose complex by centrifugation. A critical evaluation of the various fractionation procedures was provided by Whistler (1965), and Banks and Greenwood (1975).

(a) Amylose

(i) General characteristics

The structural features of amylose are well established, as are many of its characteristics and properties.

The heterogeneous nature of amylose was first revealed by Cowie and Greenwood (1957b), who observed that it can be separated into fractions with varying β-amylolysis limits, a criterion which provides a measure of the degree of

which is influenced by the size of the molecule (i.e., DP).

A study of the hydrodynamic behavior of amylose fractions by Greenwood (1960) indicated that the observed incomplete hydrolysis of amylose by B-amylase might be due to branching in the molecule. The nature of the barrier to B-amylolysis was later examined in detail by Banks and Greenwood (1967a), who confirmed the presence of a limited degree of long chain branching.

Characterization of amylose has posed some problems in view of its heterogeneous nature. Consequently, total amylose is commonly employed in the studies of properties of amylose, with B-amylolysis and viscometric determinations (in dilute alkali solution) providing the best means for such investigations (Greenwood, 1970). The latter is particularly useful in the assessment of the molecular size of amylose, a characteristic profoundly influenced by the maturity of the plant at the time of starch isolation (Geddes et al., 1965). Potato starch amylose, isolated from mature tubers, has an iodine binding capacity (IBC) of 19.5%, a B-amylolysis limit of 76%, and a limiting viscosity value (η) in 1 M KOH of 410 ml/g, which corresponded to a DP of 3000 (Greenwood and Thomson, 1962).

Phosphate, commonly associated with the amylopectin component, esterifying the C_6 position, has been reported to be present in amylose at a frequency of 1 phosphate group per 2400 glucose units (Peat et al., 1952a). The

significance of this finding, however, has not yet been explained.

(ii) Formation of inclusion complexes

A predominant characteristic of amylose is its ability to interact with polar organic substances (monoglycerides or fatty acids), flavor substances, and iodine resulting in the formation of insoluble inclusion complexes. The reaction with polar organic solvents is used to advantage in selective precipitation and purification of amylose from starch dispersions (Gilbert et al., 1964). Interaction of emulsifying agents with amylose is well known (Legendijk and Pennings, 1970; Coman et al., 1961). This interaction has found extensive application in food manufacturing practices, notable examples being the bread industry (van Lenhuysen and Blanbestijn, 1974) and dehydrated potato granule manufacturing (Hadziyev and Steele, 1976). Coman-Iosefi and Solms (1973) conducted an investigation on the formation of inclusion compounds of starches with flavor substances. Of the four interactions mentioned, the interaction of amylose with iodine is undoubtedly the most widely investigated.

Amylose, upon reaction with iodine, produces a blue-colored complex, which, in the solid crystalline state, has been shown by X-ray diffraction to possess a helical character, with the iodine molecules in the central channel of the helix (Rundle and French, 1943). The viscosity study of Banks and Greenwood (1971) provided support to this concept in light of the observation that addition of iodine

and butanol to amylose in neutral aqueous solution is invariably accompanied by a pronounced decrease in viscosity. The authors attributed this to the ability of the complexing agent to force a helical conformation upon amylose, thereby causing a large decrease in the hydrodynamic volume of the macromolecule and, thus, the observed decrease in viscosity. This explanation is based on the assumption that amylose in neutral aqueous salt solution has no pronounced helical character.

The reaction of amylose with iodine has formed the basis for amylose determination in starch samples, generally by potentiometric iodine titration. IBC, as defined by Banks et al. (1971), is "the weight (mg) of iodine bound by 100 mg polysaccharide at zero free iodine concentration".

Banks and Greenwood (1975) indicated that the role played by the iodide ion in the amylose-iodine interaction is obscure, despite the realization that it must be present in aqueous solution before complex formation can occur. However, it was noted that iodide ion is not required for blue color development in crystalline amylose in the "V" or helical configuration. This led to the suggestion that, in aqueous solution, iodide ion might serve to bring the amylose molecule into a configuration favorable for iodine-bonding.

On a molecular level, it has been suggested that the helical amylose structure is made up of glucose residues with C1 chair conformation (Rossotti, 1959). The postulate

also accounts for the interaction between the D-glucosidic oxygen, the oxygen on C_2, and the iodine.

Many other models of the amylose-iodine complex have been proposed to help clarify the nature of amylose-iodine interaction. These were adequately examined by Foster (1965) and Banks and Greenwood (1975) in their reviews. Despite the fact that doubts have been raised concerning the validity of some of the theories proposed, they have nevertheless contributed significantly to the understanding of amylose-iodine interaction.

(iii) Behavior of amylose in solution

This particular aspect has been accorded a great deal of attention in starch research, as it aids in the understanding of the subtle details of the structure of the macromolecule. A sound knowledge of the conformation of the constituent glucose unit of amylose is a prerequisite, as the D-glucopyranose ring conformation has a profound effect on the configuration of the amylose molecule in solution (Hybl et al., 1965).

Reeves (1954) concluded from his study on the solubility of amylose in cuprammonium that recrystallized amylose contains two boat-form ring conformations, namely B1 and 3B. However, in the presence of alkali, transformation from two ring-forms to a single ring-form takes place. This was attributed to the tendency of a ring hydroxyl group, with axial orientation relative to the plane of the ring, to assume an equatorial position upon dissociation.

The postulate of Holló et al. (1961) favored the presence of a chair conformation, C1, as well as the 3B conformation in amylose, with C1 conformation being the predominant form in native amylose; while, in alkali amylose and retrograded amylose, the 3B conformation predominates. The authors stated that, unlike the C1 conformation, the 3B conformation does not confer a helical structure to the amylose chain. However, nuclear magnetic resonance studies conducted by Rao and Foster (1965) did not detect any change in the ring conformation of glucose and its oligomers with pH changes.

In general, the C1 conformation is considered the most favorable, both in the solid state (Greenwood and Rossotti, 1958; Hybl et al., 1965) and in solution (Rao and Foster, 1963a). Furthermore, the energy of the C1 conformation has been shown to be lower than that of any other conformation (Rao et al., 1967). Consequently, as pointed out by Banks and Greenwood (1975), a model of amylose consisting of glucose residues in the C1 conformation should be employed in the interpretation of the solution behavior of the macromolecule.

A divergence of opinions exists concerning the configuration and behavior of the amylose molecule in aqueous solution. As reviewed by Banks and Greenwood (1975), three basic models have been proposed: (a) the random coil model, characterized by a complete lack of tertiary structure in the molecule, and the assumption that

a helical configuration occurs only upon complexation with iodine and other complexing agents (Banks and Greenwood, 1967b); (b) the interrupted, tightly-wound helix model advanced by Szejtli et al. (1967), which depicts amylose as a molecule composed of helical segments, with the helical regions stabilized by intramolecular hydrogen bonds, each segment consisting of about 120 glucose units with limited regions of random coil interspaced between the segments; and (c) the deformed helix model developed by Rao and Foster (1963b), which describes the polymer in aqueous solution as consisting of relatively stiff, worm-like coils with an essentially imperfect or deformed helical backbone structure stabilized by intramolecular hydrogen bonds.

Maywald et al. (1968), on the basis of the observation that a progressive increase in temperature is not accompanied by an increase in viscosity, favored the concept of an essentially non-helical molecule, probably randomly tangled and twisted by the bond angle of the α-1,4 glucosidic linkage, and not subject to expansion by heat treatments. Verification of this concept came from Banks and Greenwood (1968a,b), who, from hydrodynamic studies of amylose in neutral and alkaline aqueous solvents, presented evidence for the absence of rigid helical segments in the amylose molecule in aqueous solution. They also suggested that the helices, if present in amylose, are not compact in nature, as suggested by the interrupted helix and deformed helix models. This indicates that the helical character of

amylose in solution is not a consequence of intramolecular hydrogen bonding, but, rather, is attributable to the α-1,4 linkages.

On the other hand, evidence is available concerning the existence of helices in amylose in solution. The most substantial proof came from the viscosity study of amylose by Rao and Foster (1963b) in which there was a drop in the intrinsic viscosity of a neutral aqueous solution of amylose at pH 12, followed by a subsequent increase -- behavior which the authors ascribed to helix-coil transformation. Supporting evidence of this concept was given by Erlander (1968), Erlander and Griffin (1967), and Erlander and Purvinas (1968).

The finding of Casu et al. (1966), using nuclear magnetic resonance spectroscopy, that intramolecular hydrogen bonds exist between the hydroxyls at C_2 and C'_3 of contiguous glucose units in amylose in dimethylsulfoxide solution -- evidence supporting a helical structure for amylose in this solution -- was nevertheless considered inadequate as support for the helical model (Banks and Greenwood, 1975).

In an attempt to reconcile the discrepancies reported by previous authors, Senior and Hamori (1973) proposed an extended-helix model characterized by loose, extended helical regions interrupted by short random coil regions. Contraction of the loose helical regions of the polymer structure would explain the intrinsic viscosity decrease

(representing a conformation change of the macromolecule) observed upon complexation with iodine. The model would also be compatible with the reported pronounced decrease in the intrinsic viscosity of aqueous amylose solutions around pH 12 (Erlander et al., 1968; Rao and Foster, 1963b). The decrease would be due to the breakdown of the loose helical regions of the molecule caused by electrostatic repulsion arising from dissociated hydroxyl groups of the glucose units. The kinetic study of Thompson and Hasori (1971) is also in excellent agreement with such a model. Their observation that addition of iodine to already formed iodine-amylose complex results in fresh nucleation and rapid growth of newly complexed regions, rather than in growth of the existing polyiodine chains, was interpreted as a valid indication of the presence of alternating sections of regions suitable (loose helix) and not suitable (random coil sections) for rapid complexation reactions.

The controversial nature of the entire subject is obvious. The extensive review by Banks and Greenwood (1975) is highly recommended for further details on this issue.

(iv) Retrogradation

Retrogradation, a phenomenon characterized by the association of starch molecules into organized insoluble aggregates, is most commonly associated with the amylose component of starch (Foster, 1965). This phenomenon was discussed in substantial detail by Foster (1965) and Collins (1968). Foster pointed out that retrograded starch and

retrograded amylose are both microcrystalline in nature, and that they both give rise to the characteristic B-type X-ray diffraction patterns. Although a complete elucidation of the process of retrogradation is not easily achieved, owing to its complex nature, it is believed to "involve interaction between neighboring molecules, mutual alignment, expulsion of water, and formation of new intermolecular forces" (Foster, 1965), which are most likely hydrogen bonds (Collins, 1965).

The process, as pointed out by Foster, is subject to the influence of a number of factors, of which the molecular weight of amylose is of the greatest importance. High molecular weights have been shown to be accompanied by a decreased rate of retrogradation (Lansky et al., 1949). The rate of retrogradation also varies with different origins of starch (Loewus and Briggs, 1957). Also, slower retrogradation at pH 4 than at pH 6.5 demonstrates the profound influence of pH (Paschall and Foster, 1952).

Loewus and Briggs (1957) followed the retrogradation of amylose in dilute solution by measuring the change in the IBC of amylose. They observed that the retrogradation process consists of an initial lag phase, followed by a phase during which the rate accelerates rapidly in an autocatalytic manner until complete retrogradation is attained. In addition, they reported the effects of salts and additives on the rate of retrogradation, and concluded that salts of monovalent anions and cations retard

retrogradation, with iodide and potassium being the most effective of the anions and cations, respectively. Cations of high valency, however, were found to accelerate the retrogradation process. The authors also noted an acceleration of the process at lower temperatures.

Leach (1965) reported that, in addition to the concentration and the chain length (molecular weight) of amylose, another important factor which could markedly influence retrogradation was the state of dispersion of the amylose chains. Furthermore, there was an inhibition of retrogradation when substituent groups were introduced into starch molecules. These groups manifested their effects by preventing parallel alignment and association of the starch chains. Due to insoluble complex formation with amylose, prevention of retrogradation in starch-based foods can also be achieved through the use of emulsifiers (Krog, 1973).

(b) Amylopectin

(i) Fine structure

Amylopectin has not been extensively investigated. Amylopectins are highly polymeric, differing structurally from amylose in the extent of branching.

Three classical models proposed for amylopectin structure were discussed in a review by Banks and Greenwood (1975), and, more recently, by Greenwood (1976). They are: (a) the laminated structure of Haworth et al. (1937); (b) the herringbone structure, advanced by Staudinger and Husemann (1937); and (c) the randomly-branched structure of

Meyer and Bernfeld (1940).

The amylopectin structure can be considered to consist of a number of different kinds of chains designated A-, B-, and C-chains (Peat et al., 1952b), with A-chains representing those in which the glucose residues are linked only through α-1,4 linkages; B-chains with substituents at the C6-hydroxyls; and the single C-chain carrying the only reducing end group in the molecule. The three models can be visualized as structures with a ratio of A- to B-chains close to zero, infinity, and one, respectively.

A revision of the Meyer model was suggested by Gunja-Smith et al. (1970). The revised structure, while still maintaining an A:B-chain ratio of unity, differs from Meyer's model in that only half of the B-chains bear substituent A-chains, while half have their nonreducing chain ends inside the molecule instead of at the surface. Marshall and Whelan (1974) later revised the model in relation to amylopectin structure, and suggested an A:B-chain ratio of 2:1, thereby indicating that each B-chain carries, on the average, three substituent chains, which may be A- or B-chains. Diagrammatic representations of all the above models are provided in Figure 6.

A recent contribution to the knowledge of the fine structure of amylopectin was that by Robin et al. (1974), who, based on a study on Lintnerized potato starch, proposed a potato amylopectin structure consisting of alternating compact crystalline areas of chain clusters with a DP of 15,

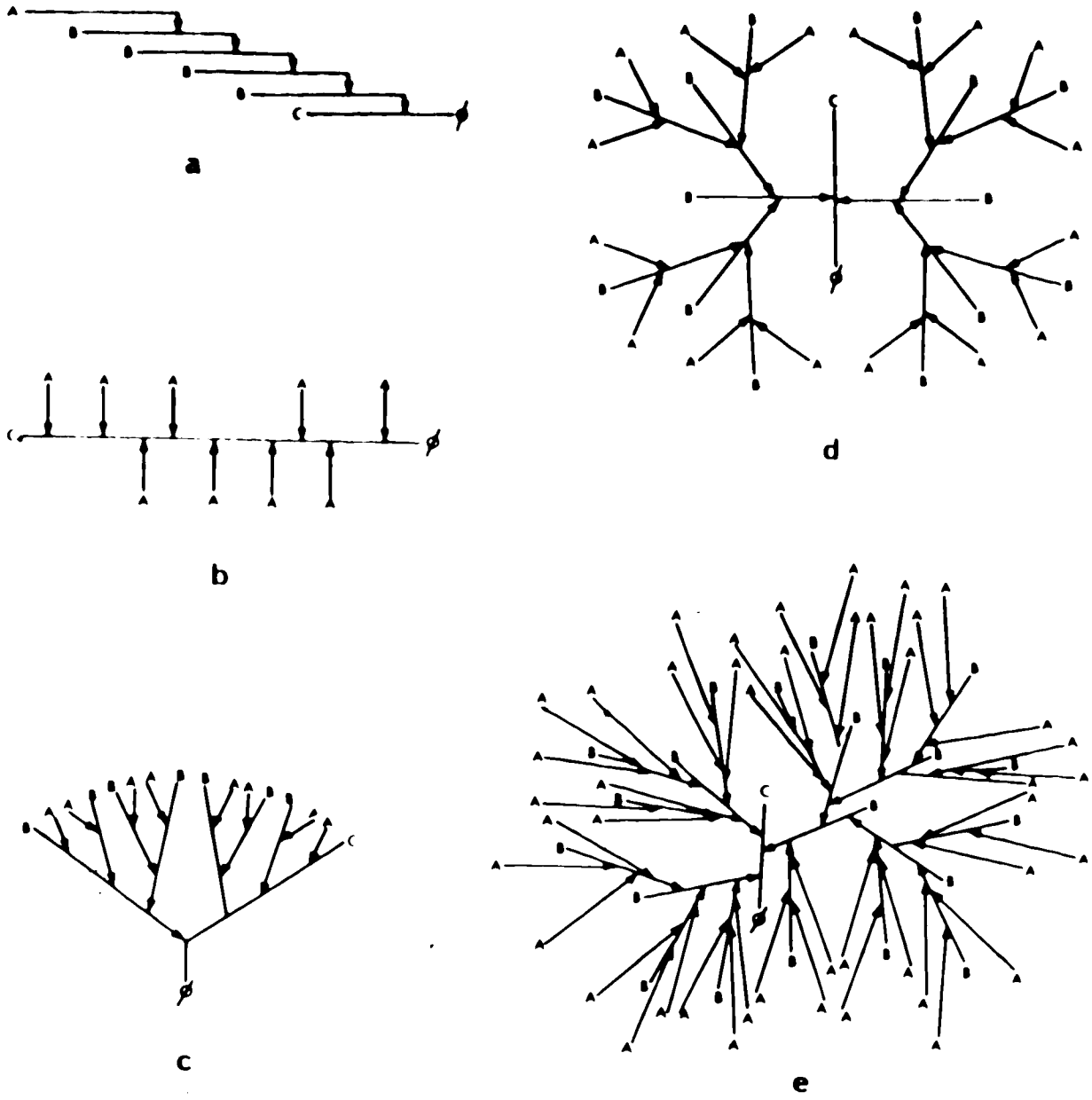

Figure 6. Diagrammatic representations of various proposed models for amylopectin structure: (a) laminated structure (Haworth et al., 1937); (b) herringbone structure (Staudinger and Husemann, 1937); (c) randomly branched structure (Meyer and Bernfeld, 1940); (d) revised Meyer-Bernfeld model (Gunja-Smith et al., 1970); (e) another revised Meyer-Bernfeld model (Marshall and Whelan, 1974).

--- represents chain of α-1,4 linkages; ↓ : α-1,6 linkages; ∮ : reducing end-group. A-, B-, and C-chains are as defined by Peat et al. (1952b).

and less compact intercrystalline areas rich in α-1,6 linkages. Such a structural scheme for amylopectin provides confirmation for the cluster model proposed by French (1972).

No conclusive evidence, however, has yet been presented with regard to the structural characteristics of amylopectin. Nevertheless, heterogeniety in branching density within amylopectin has been shown (Roberts and Whelan, 1960).

(ii) Other characteristics

No general consensus exists on the order of magnitude of the molecular weight of amylopectin. A value of 36 x 10^6 was reported by Witnauer et al. (1955), using the light scattering method, whereas Greenwood (1960), employing the same technique, obtained a molecular weight of 50 x 10^7 which was claimed to be more representative of native amylopectin.

Of all the characteristics of amylopectin, its average unit chain length and β-amylolysis limit are considered to be the most important (Greenwood, 1970). A typical sample of amylopectin from potato starch was found to possess the following properties: average length of unit chain, 24 glucose units; β-amylolysis limit, 56%; limiting viscosity number, η , in 1 M KOH, 160 ml/g; and a P content of 0.04% (Greenwood and Thompson, 1962).

While no pronounced change in the P content, the β-amylolysis limit, and chain length of amylopectin can be

detected throughout the growth period of the potato, a significant increase in its molecular weight is apparent with an increase in starch maturity (Geddes et al., 1965). The average length of unit chain has been reported to depend largely on the botanical species, rather than the variety from which the starch was obtained (Greenwood, 1956).

P in potato starch, found mainly associated with the amylopectin component, has received considerable attention owing to its influence on starch properties. As Posternak (1951) indicated, P occurs in the form of orthophosphate esterified with the C_6-hydroxyl group of the glucose residues.

The esterified ionic phosphate groups impart a polyelectrolyte character to amylopectin, thus influencing its hydrodynamic behavior in solution. Greenwood (1960) showed that salt concentration significantly influences the viscosity of amylopectin solutions. The volume of the molecule was found to be larger in water than in salt solutions. Greenwood attributed this to screening of the ionic phosphate group of the anionic sites, and contracting of the molecule. The profound influence of phosphate groups on the behavior of amylopectins in solution was verified by Maywald et al. (1968).

Neutral aqueous solutions of amylopectin are very stable (Foster, 1965), but degradation of the molecule will take place in acidic or alkaline media (Lansky et al., 1949). Unlike amylose, amylopectin does not retrograde

readily, although it may do so at low temperatures (Manks et al., 1973).

Amylopectin exhibits relatively low IBC under normal conditions of potentiometric titration. The presence of a large number of branch points within the macromolecular structure is thought to be the cause (Greenwood, 1970). However, the external branches are believed to bind iodine in a manner similar to short-chain amylose molecules (Foster, 1952).

J. Swelling, gelatinisation, and pasting characteristics of starch

Various aspects of this subject were reviewed in detail by Leach (1965).

Native starch is insoluble in cold water because of the molecular arrangement within the grain. Instead, reversible swelling occurs, the process being aided by the easy access of water to the micellar network of the grain. The water sorption capacity of starch under such conditions is limited; the extent of swelling being largely governed by such characteristics as molecular weight, degree of branching, the length of the outer branches in amylopectin, and the relative proportion of amylose to amylopectin -- all of which play a role in determining the strength and character of the micellar network within the starch grain.

Heating of an aqueous suspension of starch grains brings about an initial stage of reversible swelling during which the appearance of the grains is retained. However,

when the gelatinization temperature is approached, there is irreversible tangential swelling of the grains, and loss of birefringence (an indication of the breakdown of grain crystallinity).

The irreversible swelling process also results in the solubilization of starch molecules, which are partially leached from the swollen grain. Examination of the swelling and solubilization patterns of various starch species led Leach et al. (1959) to postulate two sets of bonding forces within the grain of cereal starches, and one set of forces in tuber starches such as potato, in which there is a rapid single-stage swelling at relatively low temperature, indicating weak but uniform internal associative forces within the grain. [redacted] presence of ionizable esterified phosphate groups [redacted] ato starch has been held partly responsible for its exceptionally high extent of swelling.

The gelatinization temperature is usually reported as a range, owing to the fact that, for a given starch grain population of the same species and cultivar, the grains do not gelatinize simultaneously. The variation in grain size, architecture, and composition, as well as cohesive forces within the starch grain has been emphasized by Banks and Greenwood (1975).

The gelatinization temperature range is profoundly influenced by the source of the starch, and, with potato starch, varietal differences may also be important (Leach, 1965). The gelatinization temperature range reported for

potato starch is 56-66°C.

External influences which affect the gelatinization temperature are pH, and the presence of certain salts and compounds. A marked change in gelatinization temperature is observed when the pH values are outside the range of 5-7 (Leach, 1965). The repression of gelatinization can be readily achieved by the addition of sodium sulfate, whereas sodium nitrate or urea bring about an increase in grain swelling, or lowered gelatinization temperature. There is also a lowering of the gelatinization temperature as a result of esterification or etherification of starch, the extent of the effect being dictated by the degree of substitution and the nature of the substituent group.

The effect of metal cations (Ca, Cu, Al) on the swelling and gelatinization behavior of wheat starch has also been investigated (Gough and Pybus, 1973). Egg albumen, gelatin, methyl cellulose and carboxymethyl cellulose, due to their ability to compete for moisture, have been shown to affect starch gelatinization (Watson and Johnson, 1965). Furthermore, lower grain size and higher amylose content both tend to increase gelatinization temperature (Banks and Greenwood, 1959).

The ability of starch grains to undergo swelling and gelatinization, with subsequent development of paste viscosity, is of practical and technological significance. These properties of the grains are directly interrelated (Leach, 1965). Control of rheological properties of starch

pastes is readily accomplished by alteration of the organizational forces within the grain as a result of change in the swelling and gelatinization behavior of the starch (Greenwood, 1970). This has led to the development of starches, modified to varying degrees, which have found great commercial application. Introduction of substituents into starch (giving etherified or esterified starches) causes a weakening of associative forces within the grain, thus increasing swelling and lowering gelatinization temperature, and yielding a paste of improved uniformity (Greenwood, 1970). Cross-linked starches, on the other hand, with reinforced associative forces within the structure, exhibit marked reduction in grain swelling and solubilization, with a consequent decrease in viscosity. Use of cross-linked starches is desirable if viscosity breakdown is to be avoided during cooking (Leach, 1965), or if grains with enhanced shear resistance are required (Radley, 1976).

Starch swelling and solubilization are also profoundly affected by surfactants and fatty adjuncts. Gray and Schoch (1962) found that polar surfactants, such as higher fatty acids and monoglycerides, restrict the swelling and solubilization of corn, potato and waxy sorghum starches owing to the ability of the surfactants to form inclusion complexes with amylose. Therefore, surfactants are widely used in production of dehydrated potato flakes and granules.

III. EXPERIMENTAL

Potatoes

Raw potatoes used were cultivar Netted Gem (Russet Burbank) grown in Southern (Vauxhall), Central (Winterburn), and Northern (Peace River) Alberta, with specific gravities of 1.080-1.110. The potatoes, obtained soon after harvest, were stored at 4°C. The tubers were reconditioned at room temperature for 10 days prior to use. Tubers used for the starch grain size distribution study were from the 1977 harvest year, while all others were from 1978.

Chemicals

Amyloglucosidase and bacterial amylase, with activities of 150 and 120 anhydroglucose units per ml, respectively, were obtained from Van Waters & Rogers Ltd., Lachine, Qué. The Glucostat reagent set was from Worthington Diagnostics, Freehold, NJ. Standard glucose solutions containing 10 mg glucose per ml in 0.1% (w/v) benzoic acid were obtained from Sigma Chemical Co., St. Louis, MO. Buffered formalin phosphate solution (10%; pH 6.9-7.1 at 25°C) was from Fisher Scientific Co., Fair Lawn, NJ. Glutaraldehyde (10%), propylene oxide, lead citrate, and uranyl acetate -- all of EM grade -- were from Polysciences, Inc., Warrington, PA. Aqueous OsO_4 (4%; EM grade), araldite resin 502, DDSA (dodecenyl succinic anhydride), and DMP-30 (dimethylaminomethylphenol) were supplied by Stevens Metallurgical, New York, NY. All the other chemicals used in this study were of reagent grade, and were supplied by

Fisher Scientific Co.

Equipment

Mineral composition was analyzed with an atomic absorption spectrophotometer, Model 153 (Instrumentation Laboratory, Inc., Lexington, MA).

Centrifuges used were: Sorvall SS-1 Superspeed Angle Centrifuge (Ivan Sorvall Co., Inc., Norwalk, CT), International Centrifuge, Size 2 (International Equipment Co., Boston, MA), Beckman Model J21B Refrigerated Centrifuge (Beckman Instr. Inc., Palo Alto, CA).

Colorimetric measurements were made with a Unicam SP 1800 Spectrophotometer (Pye Unicam Ltd., Cambridge, UK), or a Beckman DBG (Beckman Instr., Inc.).

Tissue sections were prepared by a Faust hand microtome (Scientific Supply, Madison, WI), and examined with an Olympus Model BHA microscope equipped with a camera (Olympus Optical Co., Ltd., Tokyo, Japan).

The sifter employed in particle size analysis was a Model L3P Sonic Sifter equipped with stainless steel sieves, with sieve openings of 106 μm (140 mesh), 74 μm (200 mesh), 53 μm (270 mesh), and 38 μm (400 mesh), supplied by Allen-Bradley Co., Milwaukee, WI. Sieves were cleaned in a Bransonic Ultrasonic Cleaner (Branson Ultrasonics Corp., Scarborough, Cnt.).

Potentiometric titrations were carried out using a Fisher 320 Accumet expanded scale pH Meter equipped with a saturated calomel porous ceramic junction electrode, a

platinum wire electrode with a large surface area, and a stirring device fitted with a glass propeller-type blade (Fisher Scientific Co., Ltd., Fair Lawn, NJ).

The starch melting point apparatus was from Ernst Leitz, Wetzlar, W. Germany.

Freeze dryers used were: RePP Freeze Dryer, manufactured by Virtis Co., Inc., Gardiner, NY; and, for SEM work, an Edwards-Pearse Tissue Dryer from Edwards High Vacuum Mfg., Crawley, Sussex, UK.

The wide-line nuclear magnetic resonance analyzer was a Newport Mk II Quantity Analyzer manufactured by Newport Instruments Ltd., Newport Pagnell, UK.

The electron microscopes used were: 'Stereoscan' 150 scanning electron microscope (Cambridge Instruments Ltd., Cambridge, UK), and a Philips EM-200 transmission electron microscope (Philips Electronics Ltd., Oslo, Holland). Sections for TEM study were cut using a Sorvall type MT2-B Porter-Blum ultramicrotome (Ivan Sorvall, Inc., Norwalk, CT).

Other equipment used: Serological Bath and Forced Draft Isotemp Oven, both from Fisher Scientific Co., Ltd.; Precision Scientific Lo-Temptrol Water Bath (Precision Scientific, Chicago, IL); Caframo Type RZR1-64 Stirrer (Caframo Ltd., Wiarton, Ont.); and a vacuum oven from National Appliance Co., Skokie, IL.

Methods

A. Tuber characteristics

1. Size

The tubers from each location were washed and air-dried. They were then graded according to size and separated into the following three groups:

Weight (g)	Length (cm)	Diameter (cm)
110-168	7-10	4-5
169-224	10-12	5-7
225-336	12-15	7-8

2. Specific gravity

The specific gravity of each tuber, measured by its apparent loss of weight when submerged in water at 22°C, was calculated as follows:

$$\text{Sp. gr.} = \frac{m}{v} = \frac{\text{wt in air (g)}}{\text{wt in air (g)} - \text{wt in water (g)}}$$

3. Sample preparation for mineral composition and starch content determinations

Peeled potatoes were treated with 1 % $NaHSO_3$ for 2 min, and cut into slices of 1 cm thickness. The slices, placed on stainless steel trays, were frozen overnight in an air-blast freezer at -20°C. They were then freeze dried for 24 hr at <100 μ Hg pressure and 85°C shelf temperature. The dried tuber tissue samples were ground in a mortar and pestle to pass a 60 mesh sieve, and then stored in airtight containers until analysis.

4. Mineral composition

Ground, freeze-dried tuber tissue or starch samples of 2.5 g were charred at 200°C for 30 min, then ashed at 500°C for 2 hr. Each sample was then cooled, wetted with a few drops of HNO_3, and ashed for 1 hr. The residue was cooled in a desiccator, and weighed to determine total ash content. For mineral composition determination, the residue was solubilized in 6 M HCl with gentle boiling for 30 min. Analyses for Na, K, Ca, and Mg were performed in the presence of lanthanum chloride using atomic absorption spectrophotometry (AAS). P was determined colorimetrically at 830 nm as the heteropolymolybdo blue complex.

5. Starch content

The procedure used is as described by Banks et al. (1970).

About 20±0.05 mg of ground, freeze-dried tuber tissue were placed in a 10 ml centrifuge tube. Particles adhering to the side were washed down with 3 ml of 95% ethanol. The solution was then centrifuged at 14,000 x g for 15 min. The sediment was extracted 3 times at 60°C with 5 ml of 80% ethanol (after each extraction the mixture was centrifuged at 14,000 x g for 15 min, and the supernatant discarded).

$CaCl_2$ solution (pH 2.0; Sp. gr. 1.30; approximately 50%), 1 ml, was then added to the residue with stirring. A few boiling chips were added, along with 2 drops of octyl alcohol. The solution was boiled for 15 min in an oil bath at 130-135°C, then cooled to room temperature.

For enzymic digestion of starch, 2 ml of 0.05 M KOH and 4 ml of 0.1 M acetate buffer, pH 4.8, were added to the tube with mixing. Amyloglucosidase solution, 0.5 ml (equivalent to 7 units of activity), and 0.1 ml α-amylase solution (25 units of activity) were then added with gentle stirring. Incubation was carried out for 3 hr at 47-48°C. Then the contents of the tube were transferred to a 500 ml volumetric flask and made up to volume with water. The solution was filtered through Whatman No. 1 paper, and a 20 ml fraction was collected for glucose analysis after discarding the first 30 ml of the filtrate.

Quantitative enzymic determination was done using the Glucostat Reagent Set. Absorbance readings were taken at 425 nm.

6. Tuber cell size distribution

Each tuber was cut along the longitudinal axis, and 3 tissue blocks, representing the cortical, perimedullary, and pith zones, were then removed from the middle fifth of the tuber. These blocks were preserved in 10% buffered formalin phosphate solution until examination. For sectioning, each block was trimmed to fit a hand microtome. Throughout the sectioning process, water was spread on the specimen block face and the razor blade with the aid of a camel hair brush. About 10-15 sections of about 200 μm thickness from each tissue zone were then transferred onto a microscope slide. The sections were suspended in formalin solution, the solution being replenished periodically during examination

under a light microscope.

Photographic images of at least 10 different fields of view were recorded at 50x magnification. Cell measurements were carried out on enlarged photomicrographs (150x magnification). At least 4 diametric measurements were made for each cell, and the average diameter determined. The surface area and volumetric size were calculated assuming the cell to be spherical in shape.

7. Isolation of native starch grains from whole tuber

Three replicates of 3 tubers for each location-tuber size category were done for starch grain samples intended for size distribution study.

The tubers were washed, grated, and transferred to a Waring blendor. About 300 ml ice-cold 1% ammonium oxalate solution, containing 1,000 ppm $NaHSO_3$ and 1 ml of octanol, were then added. The tubers were homogenized at slow speed to a uniform consistency. The homogenate was filtered through a 107 mesh silk cloth sieve. The cellulosic residue on the sieve was reground in the presence of ammonium oxalate solution, and filtered. The grinding process was repeated until the tissue was well disintegrated. The residual pulp material was then washed with water and the filtrates combined.

Starch from the combined filtrates was obtained by centrifugation at 700 x g for 10 min. The supernatant and protein layered on the starch sediment were removed by gentle suction. Further purification of the starch was

achieved by repeated suspensions in water, centrifugation, and removal of contaminating protein.

The purified product was washed with 95% ethanol, and sedimented as before. The sediment was suspended in diethyl ether and filtered. The starch was washed with acetone, air-dried, and stored in airtight containers.

Starch samples to be used in the study of starch properties were prepared from a total of 12 tubers for each tuber category. In addition, organic solvents were omitted from the isolation procedure.

8. Starch grain size distribution within potato tuber

The sonic sifter was operated at: pulse amplitude, 5; sift amplitude, 5-7; time indicator, 30 min.

Approximately 5 g sample were placed on a weighed 106 µm sieve. After sieving, a small representative sample was removed from the sieve for examination under a light microscope. The process was repeated until thorough sifting was achieved, as indicated by the absence of smaller particles. Finally, the sieve containing the sample was weighed.

Particles which may have adhered to the sides of the spacers were brushed into the fines collector, the contents of which were then emptied onto a finer sieve (74 µm), and sifted. This procedure was repeated with the 53 and 38 µm sieves. The effectiveness of the sifter in the separation of a starch sample into various fractions is evident in Figures 7a, b, and c.

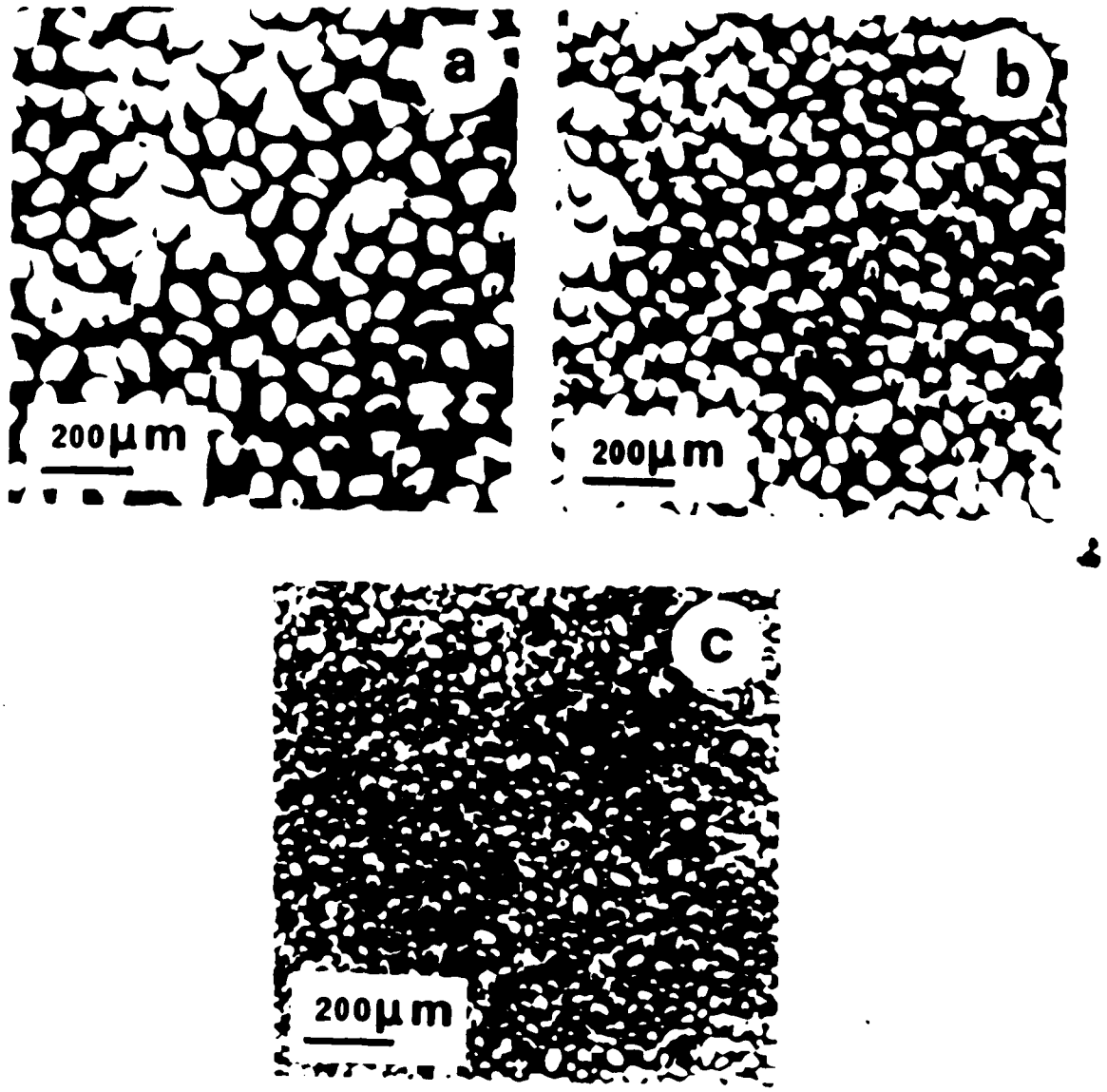

Figure 1. Scanning electron micrographs of size-graded starch grain fractions.

a. 53-74 µm

b. 38-53 µm

c. < 38 µm

b. Processing quality of tubers

(a) French fry preparation

For each of 3 processing runs, 3 tubers of each location-tuber size category were washed and hand peeled. The tubers were then treated in 1,000 ppm $NaHSO_3$ for 5 min, after which they were cut into strips (cross-sectional area: 1 x 1 cm). The strips were heated in a water bath at 70°C for 8 min, cooled in cold water for 5 min, and then blanched at 70°C for an additional 8 min. They were then drained of excess water before being fried in vegetable oil (Crisco) at 190°C for 4 min. The surface oil was drained from the French fries, which were cooled, placed on stainless steel trays, frozen overnight at -20°C in an air-blast freezer, and freeze-dried for 36 hr at <100 μ Hg pressure, and 25°C shelf temperature.

The dried product was placed in airtight brown bottles prior to being ground with a mortar and pestle. In order to reduce the moisture content to less than 4.5% (since higher moisture content would interfere with subsequent wide-line nuclear magnetic resonance measurements), the ground samples were dried in the freeze-dryer for 24 hr at <100 μ Hg pressure and 40°C shelf temperature. The samples were stored in sealed containers at 4°C. Approximately 6 g of each sample were removed for duplicate moisture determinations by heating at 105°C for 6 hr.

(b) Oil uptake determination

This was performed on the Newport Nuclear Magnetic Resonance Analyzer using the following operating conditions: R.F. level, 200 μA; A.F. gain, 138; integration mode, single shot per 32 sec.; automatic loss control, low loss; and supplementary modulation mode, on.

All samples were allowed to warm up to 22°C before analysis. The amounts of the calibration standard (Crisco oil) and the sample were 25 g and 12.5 g, respectively. Duplicates of each sample were scanned 3 times to improve precision. The percentage of oil in the sample was estimated from the ratio of its signal to the signal of the standard oil on a per g weight basis.

B. Starch characteristics

1. Amylose/amylopectin ratio

The technique employed was that of Schoch (1964a).

The reagents used were: a stock iodine solution containing KI and KCl in concentrations of 0.5 N, with approximately 2 mg of iodine per ml; and a freshly prepared 10-fold diluted iodine solution of the stock for actual titrations.

An EMF calibration curve (Figure 8) for the standard iodine solution was prepared as follows: a solution of 373 mg KCl and 830 mg KI in 100 ml water in a 250 ml beaker was titrated with iodine solution, with gentle mechanical stirring. The iodine solution was added in minute quantities, and the EMF reading was recorded after each such

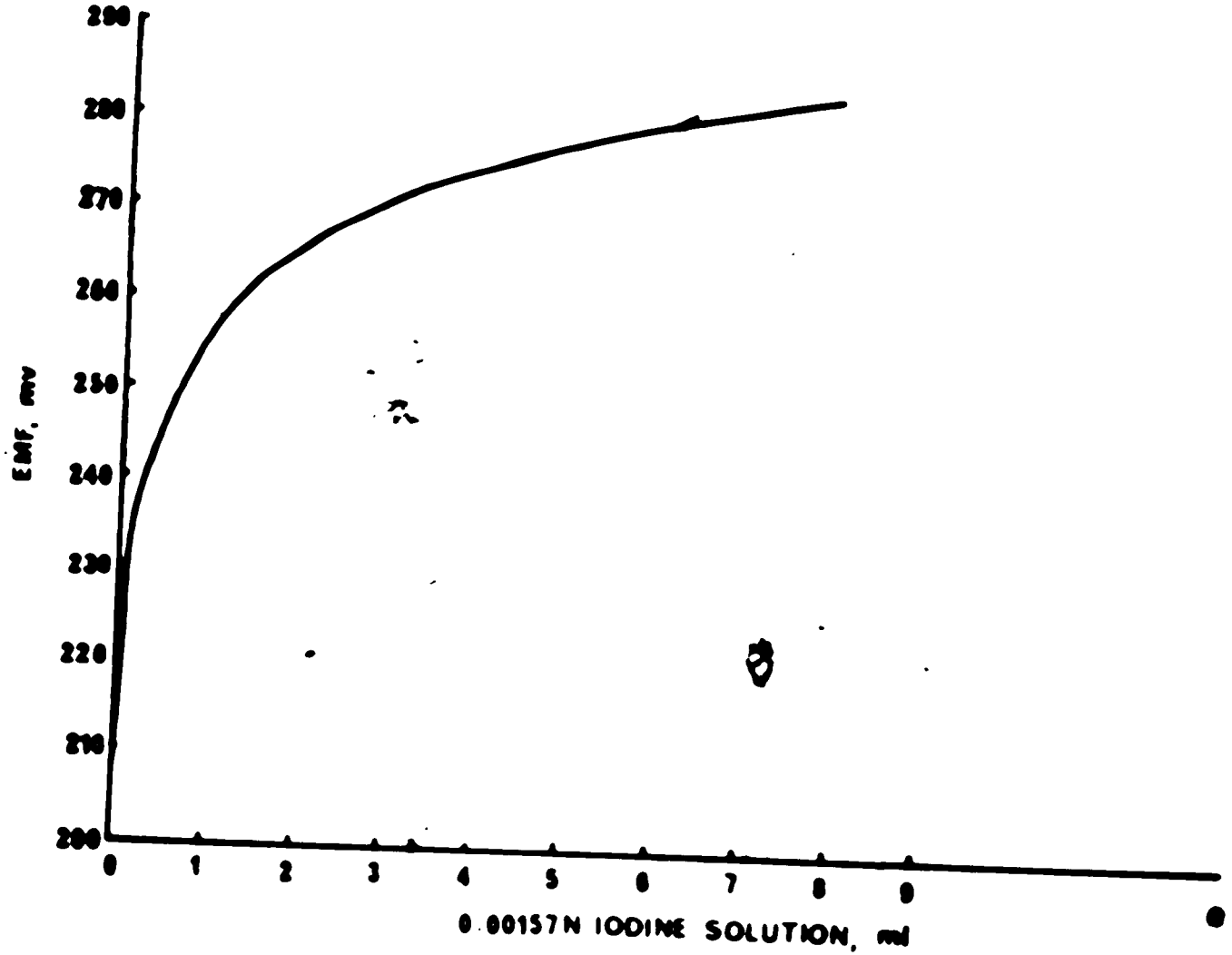

Figure 8. Standard curve of EMF versus free iodine at 30°C.

addition, allowing at least 2 min for equilibration.

For the titration of starch, about 100±0.01 mg were suspended in 1 ml of water in a preweighed 250 ml beaker. KOH solution (1.0 N), 5 ml, was then added, and the sample was ground with a glass rod to assist dispersion. The mixture was left at 4°C for 30 min, with occasional stirring. Complete dissolution was accomplished by gentle heating for 15 min, after first neutralizing the sample with 0.5 N HCl and adding 25 ml water. After cooling to room temperature, 10 ml of 0.5 N KI were added. The mixture was then neutralized to methyl orange with 0.5 N HCl. The total weight of water present was adjusted to 100.9 g, which corresponded to 100 ml at 30°C. Titration was carried out as described earlier. A typical starch titration curve is shown in Figure 9.

From the calibration and sample titration curves, values of the amounts of bound iodine were obtained for 10-15 EMF readings. IBC was determined by extrapolation of the upper slope back to the vertical axis (Figure 10). The amylose content of the starch sample was calculated using a value of 19.62 for the IBC of amylose from potato, cv. Netted Gem, as determined by Johnston et al. (1968).

2. Swelling power and solubility

The procedure used was as outlined by Schoch (1964b), with slight modifications.

Approximately 0.5 g of starch was quantitatively transferred to a 250 ml preweighed centrifuge bottle.

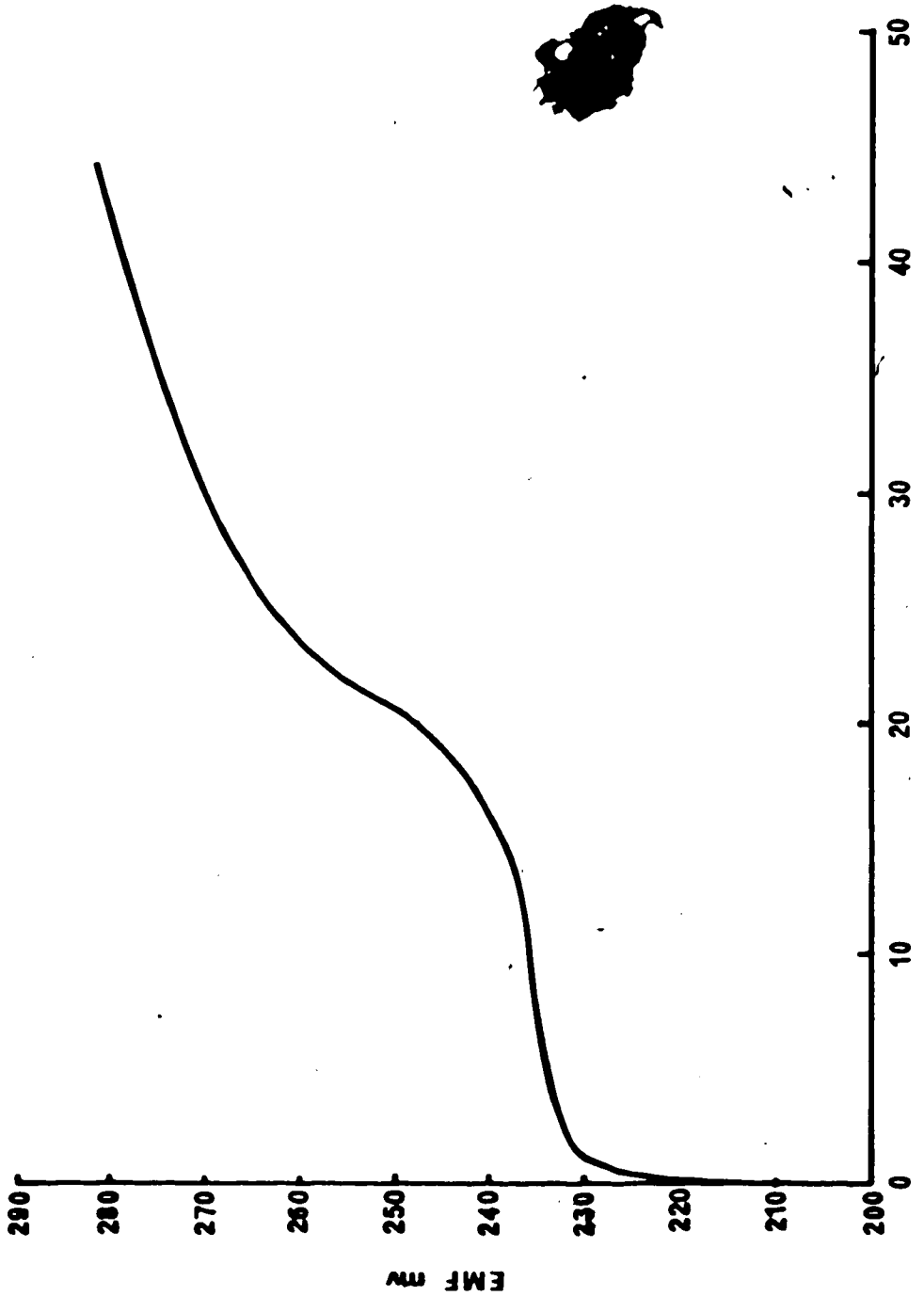

Figure 9. A typical curve for the potentiometric titration of starch with iodine at 30°C.

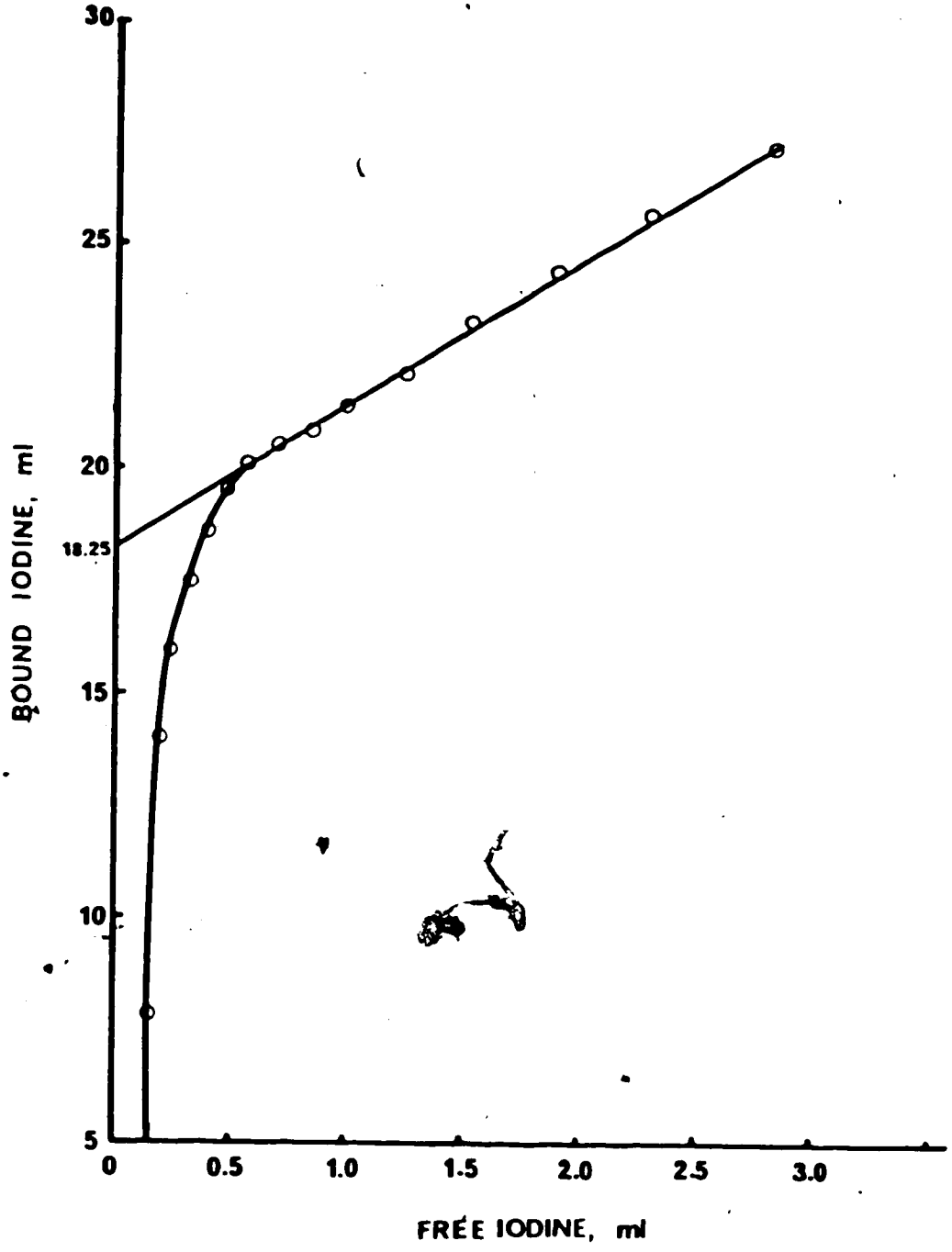

Figure 10. Plot of bound versus free iodine.

Sufficient water was added to bring the total water content to 180 g. The contents were suspended at 200 rpm with a stainless steel paddle, and the bottle was lowered into a water bath. Triplicate runs were conducted at 55, 60, 65, 70, 75, and 85°C. At the end of 30 min, the stirring motor was stopped and the bottle removed. The stirring paddle, after rinsing with a small quantity of water, was removed from the bottle, which was then wiped dry on the outside. Enough distilled water was added to bring the amount of water in the bottle to 200 g. The contents were mixed, then centrifuged at 700 x g for 15 min.

The supernatant was carefully suctioned off to within 0.5 cm of the sediment. The solubles in the supernatant were determined by evaporating duplicate 50 ml aliquots on a steam bath prior to final drying at 105°C. The remainder of the supernatant was removed and discarded.

The swelling power (SP) of the starch grains, expressed as the weight of sedimented paste per gram of starch (dry basis), after correcting for the soluble starch, is calculated as follows:

$$SP = \frac{\text{wt of sedimented paste, g} \times 100}{\text{wt of sample, g} \times (100 - \% \text{ solubles, dry basis})}$$

3. Mineral composition

The ash content of starch samples was determined as described earlier for freeze-dried and ground whole tuber tissue.

Preparation of samples for mineral composition

determination involved two methods: wet ashing with $HClO_4$, and the ion-exchange method developed by Winkler (1960). For the former, Na, K, Ca, and Mg were analyzed by AAS, while P was determined colorimetrically at 830 nm as the heteropolymolybdo blue complex.

With the ion-exchange method, 5 g starch on a sintered glass funnel were washed thoroughly with 0.1 N HCl, followed by water, and the filtrate collected for cation analysis by AAS. The starch residue was slurried with 5 ml 0.02 N NaOH, then more NaOH was added by buret until the indicator (2 drops of bromothymol blue) changed color from pale yellow to green-blue. Water was then added, along with an amount of 0.02 N NaOH 3 ml greater than that already consumed. This neutralized the secondary and tertiary H's of the starch phosphoric acid groups. The excess alkali was washed out with water from the starch with filtration, and titrated with 0.02 N HCl using phenolphthalein as indicator. The starch P content was calculated by the equation:

$$P, \text{ mg\%} = ml_{NaOH} \times 0.30974 \frac{\text{mg P}}{ml_{NaOH}} \times \frac{100 \text{ g}}{\text{Wt. of starch (dry basis), g}}$$

4. Gelatinization temperature

Starch grain samples, size-graded (74-106, 53-74, 38-53, 20-38, and <20 μm), were studied under a plane polarized light microscope at a magnification of 100x. A small amount of sample in a drop of water was spotted on a glass slide. This was covered with a cover slip, the edges of which were sealed with heavy mineral oil to minimize

movement of grains during heating. The rate of temperature increase was 2 C^0 per min. Recordings were made of the temperatures corresponding to the loss of birefringence of the first and the last grain in the chosen field of view. Determinations were made in triplicate.

5. SEM study of the gelatinization process

Preparation of samples was adapted from the method developed by Hill and Dronzek (1973). A starch suspension (5 g starch in 200 ml water) was gently stirred while being heated at a rate of approximately 2 C^0 per min.

Aliquots of 20 ml were withdrawn at 2 C^0 intervals in the range of 56-70°C, transferred to 50 ml centrifuge tubes, and cooled in an ice bath prior to centrifugation at 5,000 x g for 15 min at 4°C. The supernatant was discarded, the starch sediment washed with distilled water, and the centrifugation repeated.

Samples of starch sediments were transferred to liquid Freon-12 cooled with liquid nitrogen. The frozen samples were then dried overnight in brass boats in a freeze drier at -80°C.

The samples were mounted on circular aluminum stubs with double-sided adhesive tape, and shadowed with 20 nm of gold. Examinations were performed at an accelerating potential of 10 kV.

6. Transmission electron microscopy study of starch in situ

Raw, and steam-cooked potato tissues from the cortex region of the tuber were examined. The tissue was cut into cubes of 1 mm, fixed in 3 % phosphate buffered glutaraldehyde solution (pH 7.0) for 6 hr at 4°C, and washed 3 times with 0.1 M phosphate buffer, pH 7.0. The first two washings were for 15 min, and the last for 30 min. The samples were post-fixed in 2% OsO_4 in phosphate buffer for 6 hr at 4°C, rinsed 3 times with buffer (30 min each time), and dehydrated at 4°C with 50, 70, 80, and 95% ethanol at 30 min intervals. This was followed by treatment with absolute ethanol overnight at 4°C, and an additional treatment for 1 hr at 22°C. All subsequent treatments were carried out at 22°C. The samples were treated with a mixture of absolute ethanol and propylene oxide (1:1 v/v) for 45 min before infiltration with 3 changes of propylene oxide at 45 min intervals, with occasional stirring. Treatment with a mixture of propylene oxide and an araldite mixture (consisting of DDSA, araldite resin 502, and DMP-30 in a ratio of 49:49:2 v/v/v) was carried out for 3 days, with periodic stirring to aid in the vaporization of the propylene oxide. The samples were then transferred to flat silicone rubber molds, aligned, and embedded in araldite mixture. The polymerization process lasted 36 hr at 65°C.

Sections of about 600 nm thickness were cut from these hardened tissue blocks with an ultramicrotome equipped with

a glass knife. These sections, mounted on 200 mesh copper grids coated with Formvar (a polyvinyl formal plastic film; 0.2% in ethylene chlori[redacted]), were stained with 2% uranyl acetate for 2 hr, and post-stained with 0.2% alkaline lead citrate solution for 4 min prior to examination in the transmission electron microscope operated at an accelerating voltage of 60 kV.

IV. RESULTS AND DISCUSSION

The results obtained were statistically analyzed using analysis of variance and Duncan's Multiple Range Test (Bowker and Lieberman, 1972). Table 4 shows the variables investigated, and their statistical significance in relation to tuber weight and growth location.

Elpeson and Paulus (1973) reported higher contents of DM and starch in larger than in smaller tubers. However, in the present study, the DM and starch contents of whole tubers (Table 5) were found to be independent of tuber weight. Our findings support the results of Ifenkwe et al. (1974), which indicate that high DM content is not necessarily associated with large tubers. Le Tourneau (1963) also found no correlation between the weight and total solids (i.e., DM) of tubers.

The present study shows that DM and starch contents are significantly influenced ($p=0.01$) by the location of potato growth (Table 4). Tubers from Southern Alberta had higher contents of DM and starch than those from Central and Northern regions, which showed similar levels. These findings are significant, since the contents of DM and starch have been positively correlated with the processing quality of tubers (Barrios et al., 1961a; Le Tourneau and Zaehringer, 1965; Maclean et al., 1966; Smith, 1975a). Utilization of tubers of high DM content (and, thus, starch content) usually provides assurance of a desirable finished fried product characterized by increased yield, crispness,

Table 4. Summary of statistical analyses.

Parameters		Tuber wt.	Location
Tuber characteristics:	DM content	NS	S1
	Starch content	NS	S1
	Cell size	S5	NS
	Grain size distribution	NS	NS
	Oil uptake, DM basis	NS	S1
Starch characteristics:	IBC/amylose content	NS	S1
	Swelling power	S5	S1

NS: not significant at p=0.05 or p=0.01

S5: significant at p=0.05

S1: significant at p=0.01

Table 5. Dry matter and starch contents of potato tubers.

Location in Alberta	Tuber wt. (g)	Dry matter content* (g)	Starch content** (%)
South	110-168	26.64±0.70***	76.06±1.16
	169-224	25.76±1.10	75.92±2.04
	225-336	26.18±1.93	75.98±1.67
Central	110-168	20.83±2.24	70.27±1.08
	169-224	21.04±1.22	71.93±1.63
	225-336	21.98±2.03	71.66±2.57
North	110-168	20.42±1.26	71.45±0.36
	169-224	20.47±1.34	70.89±2.95
	225-336	19.60±0.91	68.99±2.86

*Determined by heating 5 g sample at 55°C for 2 hr, then at 105°C for 3 hr.

**On a dry matter basis.

***In this and following tables the standard deviation values given have been doubled.

mealiness, improved flavor, and low oil uptake (Kirkpatrick et al., 1956; Maclean et al., 1966).

The textural quality of potatoes is also influenced by starch (Reeve, 1972; Moff, 1972; Mohr, 1972; Linehan and Hughes, 1969a,b,c). The amount of starch, as found by Harrison et al. (1961a), is significantly related to mealiness, i.e., the readiness of cell separation of cooked potato tissue under a shear force. Furthermore, starch, by competing with cell wall components for biosynthetic precursors (Albersheim, 1965), particularly calcium ions (Bretzloff, 1970), may affect intercellular adhesion and, thus, texture.

Increased plant population (Bleasdale and Thompson, 1968) and decreased soil fertility (Schippers, 1968) result in tubers of increased DM content. Herlihy and Carroll (1969) observed a reduced DM content in tubers grown with high rates of N and K applied, while P had the reverse effect. Gray (1972) did not observe a significant effect of plant density on DM content, a finding inconsistent with that reported by Bleasdale and Thompson (1969). The high DM content found in potatoes grown in Southern Alberta, with a closer plant spacing and lower fertilizer treatment than those from Central and Northern Alberta (Table 3), supports the results of Bleasdale and Thompson (1969) and Schippers (1968). With Southern grown tubers, it is obvious that the depressing effect of low P levels on DM content is not great enough to offset the combined positive effect of low N and a

applications.

Apart from tuber DM and starch contents, there is evidence that potato texture is related to the average tuber cell size (Harries et al., 1963; Linehan et al., 1968; Gray, 1972; Hughes et al., 1975). The cell size, expressed as the total surface area of cells per unit tissue volume, was shown by Linehan et al. (1968) to significantly correlate with intercellular adhesion. The increased adhesion associated with smaller cells was ascribed to the greater surface area of intercellular contact. The increase in cell size with tuber maturity (Hughes et al., 1975), as a consequence of a delay in harvest, is related to decreased cell surface area per unit tissue volume, a factor which can contribute to increased tuber breakdown upon cooking (Gray, 1972). The influence of tuber weight on tuber cell size, previously reported by Reeve et al. (1973), is confirmed by the data presented in Tables 6-8. Irrespective of growth location, the average cell size of the three tuber sizes analyzed tended to rise as tuber weight increased. Statistical analysis of the data (Table 4) also indicated a significant influence of tuber weight on cell size ($p=0.05$).

Furthermore, as found in this study and observed earlier by Reeve et al. (1971), cell size is significantly predetermined ($p=0.01$) by the tissue zone -- perimedullary cells are the largest, and cortical cells the smallest, with pith cells being intermediate (Figure 11a,b,c,).

Cells from the cortical and perimedullary zones, which

Table 6. Diametric measurements of cells in designated tissue zones of raw potato tubers*

Growth location in Alberta	Tuber wt. (g)	Diameter (μm)			
		Cortex	Perimedullary zone	Pith	Avg.
South	110-168	157±24	176±24	170±22	167±24
	169-224	154±21	181±25	181±25	170±27
	225-336	167±18	213±32	173±31	185±34
Central	110-168	150±20	189±31	190±25	176±32
	169-224	157±21	201±33	171±20	177±30
	225-336	161±25	198±36	182±24	178±33
North	110-168	142±18	195±24	181±19	169±31
	169-224	161±24	204±34	186±26	182±32
	225-336	152±20	217±35	191±26	182±38

*Diametric measurements of at least 50 cells.

Table 7. Surface areas of cells in various tissue zones of raw tubers*

Location in Alberta	Tuber wt. (g)	Cell surface area ($x10^4 \mu m^2$)			
		Cortex	Perimedullary zone	Pith	Avg.
South	110-168	7.9±2.4	9.9±2.8	9.2±2.4	8.9±2.6
	169-224	7.6±2.2	10.5±2.9	10.5±2.8	9.3±2.9
	225-336	8.9±1.9	14.5±4.4	9.6±3.4	11.1±4.2
Central	110-168	7.2±2.0	11.5±3.8	11.6±3.0	10.0±3.6
	169-224	7.9±2.0	13.0±4.2	9.4±2.2	10.1±3.6
	225-336	8.3±2.6	12.7±4.6	10.6±2.7	10.3±3.9
North	110-168	6.5±1.7	12.2±2.9	10.4±2.3	9.2±3.4
	169-224	8.4±2.4	13.4±4.4	11.1±3.0	10.8±3.8
	225-336	7.4±1.9	15.2±4.7	11.7±3.1	10.8±4.6

*Determined from diametric measurements of cells by assuming that the cells are spherical in shape.

Table 8. Volumetric size of cells in the cortex, perimedullary, and pith regions of raw tubers*

Location in Alberta	Tuber wt. (g)	Cell volume ($x10^6 \mu m^3$)			
		Cortex	Perimedullary zone	Pith	Avg.
South	110-168	2.2±1.0	3.0±1.3	2.7±1.1	2.6±1.2
	169-224	2.0±0.9	3.3±1.3	3.3±1.3	2.8±1.3
	225-336	2.5±0.8	5.4±2.4	2.9±1.6	3.7±2.1
Central	110-168	1.9±0.8	3.8±1.9	3.8±1.5	3.1±1.7
	169-224	2.1±0.8	4.6±2.2	2.7±1.0	3.2±1.7
	225-336	2.3±1.1	4.5±2.5	3.3±1.2	3.3±1.9
North	110-168	1.6±0.7	4.1±1.4	3.2±1.1	2.8±1.5
	169-224	2.3±1.0	4.8±2.3	3.6±1.4	3.5±1.9
	225-336	1.9±0.7	5.8±2.6	3.9±1.6	3.6±2.3

*Determined from diameter measurements of cells by assuming the cells to be spherical in shape.

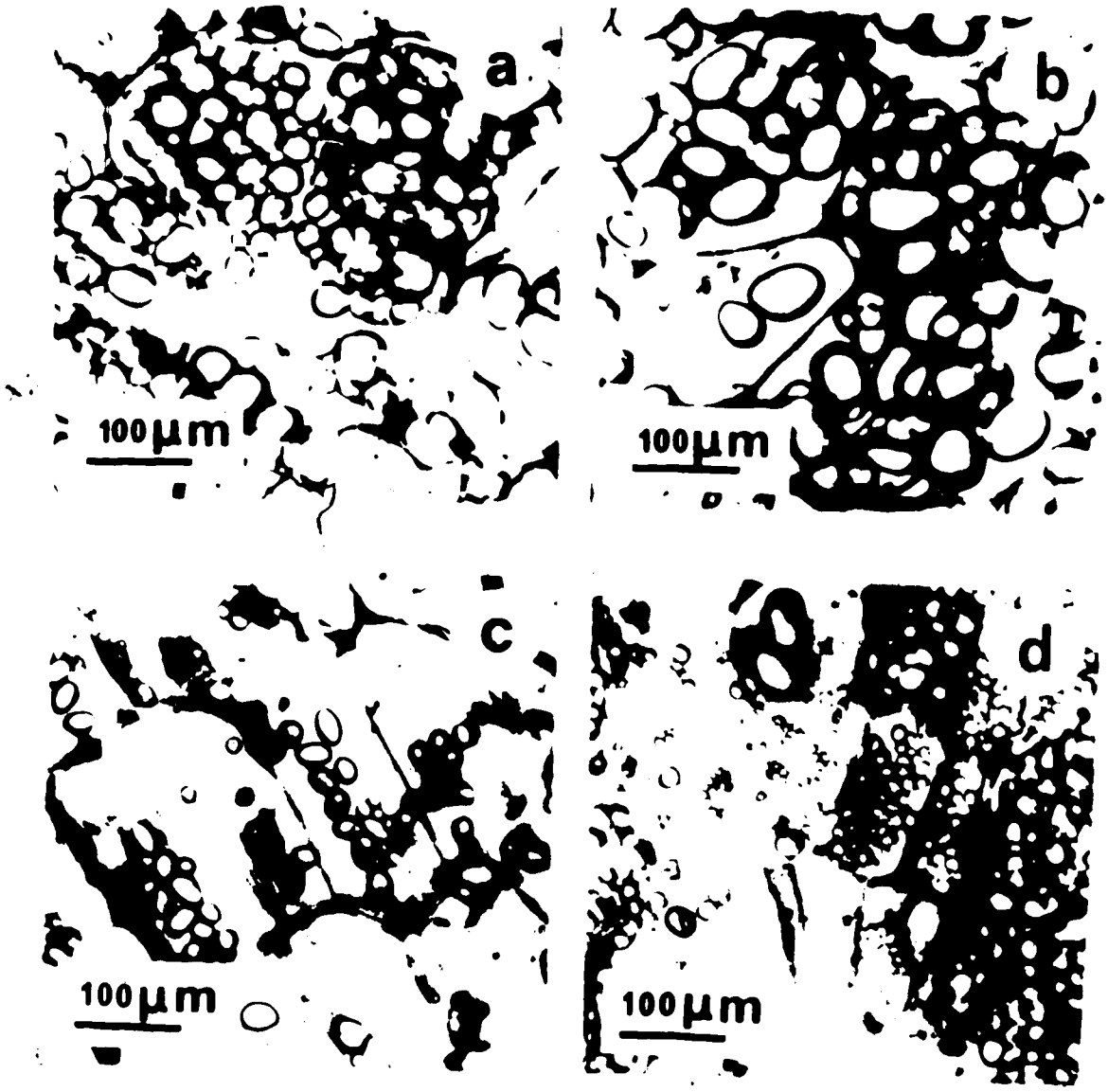

Figure 11. Light micrographs showing longitudinal sections of raw tuber tissue zones.

a. cortex
b. perimedullary
c. pith
d. vascular bundle

constitute at least 75% of the tuber size, are polyhedral in shape, while pith cells are often elongated. Thus, some errors may be introduced when the cells (elongated cells in particular) are treated as spheres in the determination of surface area and volumetric size. However, as pointed out by Reeve et al. (1971), since the length:width ratio of most elongated cells lies within the range of 3:2 to 5:4, the error does not appear to be significant. Figure 11d provides evidence for the abundance in the vascular bundle area of small starch grains which are quite resistant to gelatinization. As shown in Table 9, the gelatinization temperature is related to starch grain size, the larger the size of the grain, the more susceptible it is to gelatinization (i.e., the lower the gelatinization temperature).

The distribution of starch grain sizes in the tuber (Table 10), a factor reported to be positively related to mealiness (Barrios et al., 1963), was statistically shown to be unaffected by tuber weight or growth location (Table 4). Furthermore, the observation that the 38-53 and <38 μm fractions predominate (92.7-98.01%) in all tubers supports the earlier findings of Johnston et al. (1970).

Although no difference was found in the starch grain size distribution in tuber samples from the 1977 harvest year, starch grains isolated from tubers of the 1978 harvest showed a highly significant ($p=0.01$) variation with growth location (Table 4) of IBC and, thus, amylose content (Table

Table 9. Gelatinization temperature of size-graded starch grains*

Grain size, μm	Gelatinization temperature, °C
74-106	56-59
53-74	56-60
38-53	57-61
20-38	59-65
<20	60-70

*Determinations made on starch samples isolated from Southern Alberta grown Netted Gem potatoes.

Table 10. Starch grain size distribution of various tuber samples.

Location in Alberta	Tuber wt. (g)	Distribution (%)				
		>106µm	74-106µm	53-74µm	38-53µm	<38µm
South	110-168	0.40±0.15	0.44±0.28	2.20±0.21	44.67±1.61	52.29±1.82
	169-224	0.27±0.1	0.70±0.22	2.71±0.30	42.74±3.17	53.58±2.69
	225-336	0.35±0.15	0.47±0.37	4.53±0.24	38.07±6.95	56.58±7.53
Central	110-168	0.33±0.33	0.16±0.03	1.50±0.40	44.52±1.52	53.49±0.76
	169-224	0.43±0.29	1.10±0.20	[illegible]7	42.58±4.80	52.66±5.17
	225-336	0.29±0.15	0.24±0.06	[illegible]	38.49±1.35	57.67±1.04
North	110-168	0.43±0.36	0.64±0.79	[illegible]	64.38±8.88	31.84±7.87
	169-224	0.61±0.17	0.50±0.19	[illegible]	48.47±3.26	47.03±4.70
	225-336	0.64±0.14	1.30±0.33	[illegible]	50.67±4.64	42.03±5.58

Table 11. Iodine binding capacity (IBC) and amylose content of starches of various potato tubers.

Location in Alberta	Tuber wt. (g)	IBC*	Amylose (%)
South	110-168	4.149±0.099	21.15±0.50
	169-224	4.218±0.044	21.50±0.22
	225-336	4.254±0.077	21.68±0.39
Central	110-168	4.076±0.061	20.77±0.31
	169-224	4.193±0.083	21.37±0.42
	225-336	4.140±0.089	21.10±0.45
North	110-168	4.001±0.105	20.39±0.54
	169-224	4.049±0.105	20.63±0.54
	225-336	4.060±0.103	20.69±0.53

*On a dry basis.

11). The amylose content was independent of tuber weight. These findings and the fact that larger grains contain more amylose (Geddes et al., 1965) imply that starch grains from Southern and Central grown tubers, regardless of tuber weight, should contain higher populations of larger grains than those from Northern Alberta. Our findings are in agreement with those of some European potato cultivars -- Putz et al. (1978) also found a significant influence of year and location on starch grain size and, thus, on amylose content. The effect of fertilizer was less pronounced. An increase in the population of larger grains was observed only with N at a level above 160 kg/ha.

Storage of tubers up to 6 months at 4°C, as shown by Johnston et al. (1968), generally has no influence on starch grain size distribution. They did, however, observe a difference in the distribution pattern of Netted Gem tubers from Alberta and Manitoba, leading them to suggest that growing conditions have a marked influence on the distribution pattern of grain sizes.

The tuber ash content and its mineral composition are given in Table 12. On a dry matter basis, the ash content averaged 3.71, 4.41, and 5.17%, respectively, for tubers from Southern, Central, and Northern Alberta. Medium size tubers from all locations had the highest ash content — a finding the significance of which is not well understood. The mineral composition varied among tuber sizes and among tubers from different locations, and did not follow a

Table 12. Ash content and mineral composition of potato tubers*.

Location in Alberta	Tuber wt. (g)		Ash (%)	Mineral (mg/100g)				
				P	Ca	Mg	Na	K
South	110-168		2.68±0.30	156.7	34.8	106.2	33.8	1812
	169-224		4.91±0.13	192.6	42.2	126.8	34.1	1850
	225-336		3.55±0.11	141.3	36.9	123.0	37.9	1871
		Avg.	3.71±1.12	163.5±26.3	37.9±3.7	118.7±10.9	35.3±2.3	1844±30
Central	110-168		4.37±0.31	234.9	30.9	125.8	27.7	1904
	169-224		5.26±0.13	187.0	33.5	134.1	34.1	1916
	225-336		3.59±0.04	228.1	34.2	130.4	36.8	1871
		Avg.	4.41±0.84	216.7±26.0	32.8±1.7	130.1±4.2	32.9±4.7	1897±23
North	110-168		4.72±0.28	150.0	49.3	124.9	29.7	1844
	169-224		5.68±0.06	142.6	50.3	124.1	28.0	1892
	225-336		5.12±0.35	143.8	41.0	112.2	26.0	1955
		Avg.	5.17±0.48	145.5±3.9	46.9±5.1	120.4±7.1	27.9±1.9	1864±25

*Dry matter basis.

consistent trend. The higher average P value reported for Central Alberta potatoes may be associated with the increased P fertilization (Laughlin et al., 1974) practised in that area relative to the other two locations. Increases in K and Ca concentrations in the tuber were also reported by the same authors to accompany high rates of P application. In accordance with this report, Central Alberta tubers were found to possess the highest average K content. This effect, however, was not observed for Ca in the present study.

The mineral composition of starch grains is given in Table 13. Only 0.36% ash was found, with P, Ca, Mg, K, and Na being the predominant constituents. The content of P was highest for Central and lowest for Northern Alberta starch samples, with some variability due to tuber weight -- a result which paralleled the tuber P contents provided in Table 12. Based on the results obtained by the ion-exchange method, starch-bound P was 43.2, 39.6, and 40.6%, respectively, of the total P of Southern, Central, and Northern grown tubers. The starch P is present as orthophosphate esterified with the C_6-hydroxyl of the glucosyl residues of the amylopectin molecule. The periodicity of occurrence of the P in the amylopectin moiety, as found by Samotus and Schwimmer (1962), decreases with increasing maturity. This suggests simply an increase in starch P with maturity. Contrary to this suggestion, Geddes et al. (1965) failed to demonstrate any change in

Table 13. Mineral composition of starch from potato tubers.*

Location in Alberta	Tuber wt. (g)	Ash (%)	P (mg/100g) ion-exchange	P (mg/100g) wet ashing	(mg/100g) Ca	Mg	Na	K
South	110-168	0.36	70.6	79.5	1.87	1.84	23.8	15.1
	169-224	0.37	72.3	80.9	1.44	1.53	28.2	17.8
	225-336	0.36	69.1	80.6	1.02	1.82	22.3	20.6
	Avg.	0.36±0.09	70.7±1.6	80.4±0.8	1.44±0.42	1.73±0.17	24.8±3.1	17.8±2.7
Central	110-168	n.d.**	85.7	94.9	4.63	2.11	6.6	15.0
	169-224	n.d.	[illegible]0	91.3	1.02	1.97	8.3	19.3
	225-336	n.d.	[illegible]0	89.2	1.43	2.62	8.2	26.7
	Avg.		[illegible].0	91.8±2.9	2.36±1.97	2.23±0.34	7.7±1.0	20.3±5.9
North	110-168	n.d.	61.0	69.6	3.34	2.44	6.4	15.4
	169-224	n.d.	56.2	71.1	1.87	1.73	23.1	12.7
	225-336	n.d.	60.1	62.7	1.80	1.26	32.8	11.3
	Avg.		59.1±2.5	67.8±4.5	2.34±0.87	1.81±0.59	20.8±13.3	13.1±2.1

*Expressed on a dry matter basis.

**Not determined.

starch P content with increased starch maturity.

Of interest was the observation that the starch P values obtained by wet ashing were consistently higher than those obtained by the ion-exchange method. This discrepancy appears to be accounted for by the digestion of lysophospholipid P, which is present in native starch in the form of a clathrate compound.

The levels of Ca and Mg bound to starch phosphate appeared to be low. However, when ammonium oxalate was omitted during starch isolation, a tenfold increase in Ca content was obtained. As found by Haydar et al. (1979) in the same potato tubers, up to 50% of the Ca content is bound to starch and cell wall pectins. The levels of K were high in all tubers. Nevertheless, only 0.96, 1.07, and 0.70%, respectively, were found in starch from Southern, Central, and Northern grown potatoes.

The overall mineral composition in tubers of different weights and locations, and bound to tuber starches, though without a consistent trend or pattern, plays an important role in influencing potato texture. The role of mono- and divalent cations in mealiness and sloughiness of cooked potato tissue was emphasized by Linehan and Hughes (1969a,b), Zaehringer and Cunningham (1971), and Bartolome and Hoff (1972). Of particular interest was the finding of the latter authors that divalent cations (especially Ca) bound to starch were released upon starch gelatinization, diffusing to the cell wall, where interaction w[illegible]

carboxyl groups of pectic substances brought about increased intercellular adhesion. This mechanism is largely responsible for tissue firming in the precooking stage of potato processing into dehydrated flakes or granules.

Metal cations have a profound effect on starch itself. They influence the gelatinization temperature, and substantially decrease the swelling power (SP), solubility and viscosity of starch. These changes are due to neutralization of starch phosphoric acid with cations which bring about either a decrease in negative charge of molecules, or cross-linkages between two adjacent amylopectin chains (Mayer et al., 1979).

Less well documented is the role of metal cations in metabolic changes in starch grains of the tuber (Shekhar and Irtani, 1978). Ca and Mg were shown to promote sucrose synthesis due to their ability to activate sucrose synthetase (Delmer, 1972). On the other hand, P derived from starch, by activating starch-degrading enzymes and inhibiting those involved in starch biosynthesis, can influence the overall process of starch-sugar interconversion, a process of great importance during tuber storage.

The swelling and solubilization characteristics of the starch grains are presented in Tables 14 and 15, respectively. The swelling and solubilization patterns, as a function of temperature, are illustrated in Figures 12-17. Starch grains from small and medium sizes of Central Alberta

Table 14. Swelling power of starch from potato at various temperatures.

Location in Alberta	Tuber wt. (g)	Moisture* content (%)	Temperature (°C)					
			55	60	65	70	75	85
South	110-168	14.44	2.7±0.2	30.5±4.4	61.7±5.8	74.6±2.6	104.3±11.8	159.8±60.4
	169-224	16.00	2.5±0.1	29.9±6.3	59.7±8.1	71.7±12.2	102.3±12.0	182.0±28.4
	225-336	15.68	2.9±0.8	34.3±7.8	58.8±12.0	71.1±20.2	94.6±23.5	161.2±18.8
Central	110-168	13.59	3.2±0.2	47.5±13.6	85.1±6.0	102.1±26.5	158.0±21.9	215.5±107.0
	169-224	15.88	3.7±1.1	48.5±11.4	86.6±7.1	103.8±36.3	162.8±66.7	218.4±97.8
	225-336	14.78	4.1±1.2	39.5±2.9	63.1±9.0	74.5±15.3	104.6±27.9	163.7±51.7
North	110-168	16.07	4.1±1.4	30.9±6.0	61.7±2.7	73.5±7.2	107.2±23.1	183.3±78.7
	169-224	16.72	4.0±1.2	30.3±7.9	58.6±17.2	69.6±15.0	103.5±20.5	164.1±17.9
	225-336	18.98	3.3±1.2	33.2±5.0	62.0±8.9	75.5±13.9	100.5±25.7	178.9±30.0

Standard deviation at 95% confidence level computed from: $4.303 \times \sqrt{\left[\frac{100.S_x}{C(100-\bar{y})}\right]^2 + \left[\frac{100.\bar{x}.S_y}{C(100-\bar{y})^2}\right]^2}$

where S_x = standard deviation of mean paste weight, $\bar{x}$
S_y = standard deviation of mean percent solubles, $\bar{y}$
C = sample weight, dry basis

*Determined by drying 5 g sample at 120°C for 4 hr in vacuum oven.

Table 15. Percent solubles at various temperatures of potato starch.

Location in Alberta	Tuber wt. (g)	Temperature (°C)					
		55	60	65	70	75	85
South	110-168	0.9±0.5	9.4±1.2	17.6±0.5	20.3±0.4	24.3±1.0	30.8±4.1
	169-224	0.0±0.0	7.0±1.6	16.7±1.5	18.9±2.3	21.8±1.4	32.2±1.8
	225-336	0.9±0.8	8.9±3.3	15.1±2.8	18.1±3.9	20.4±2.6	29.5±1.4
Central	110-168	2.0±0.4	12.9±4.2	19.1±0.9	22.0±2.3	30.5±1.4	42.8±4.5
	169-224	1.3±1.1	13.0±3.5	18.3±0.8	21.1±4.6	32.1±4.6	38.8±3.8
	225-336	2.3±1.5	10.2±1.0	14.3±1.7	17.6±2.5	21.7±3.5	31.6±3.5
North	110-168	2.3±0.4	9.5±1.4	16.0±0.4	19.3±0.9	23.7±1.9	36.4±3.2
	169-224	2.2±2.6	8.3±2.8	13.5±4.3	18.0±1.7	22.3±2.5	31.4±0.8
	225-336	1.5±1.5	9.0±2.0	16.1±0.6	19.6±2.3	21.2±3.0	30.4±1.8

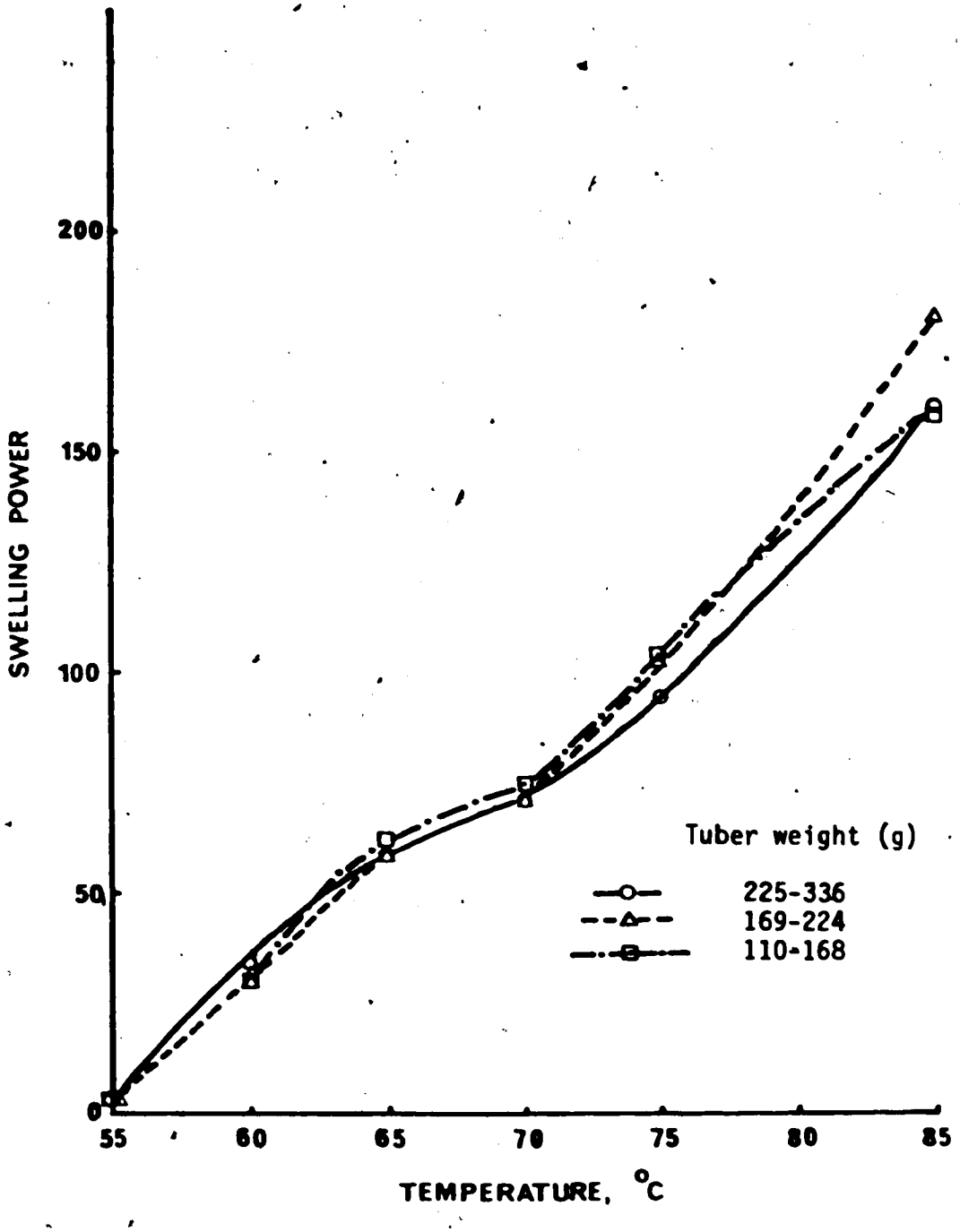

Figure 12. Swelling patterns of starch from Southern Alberta potato tubers.

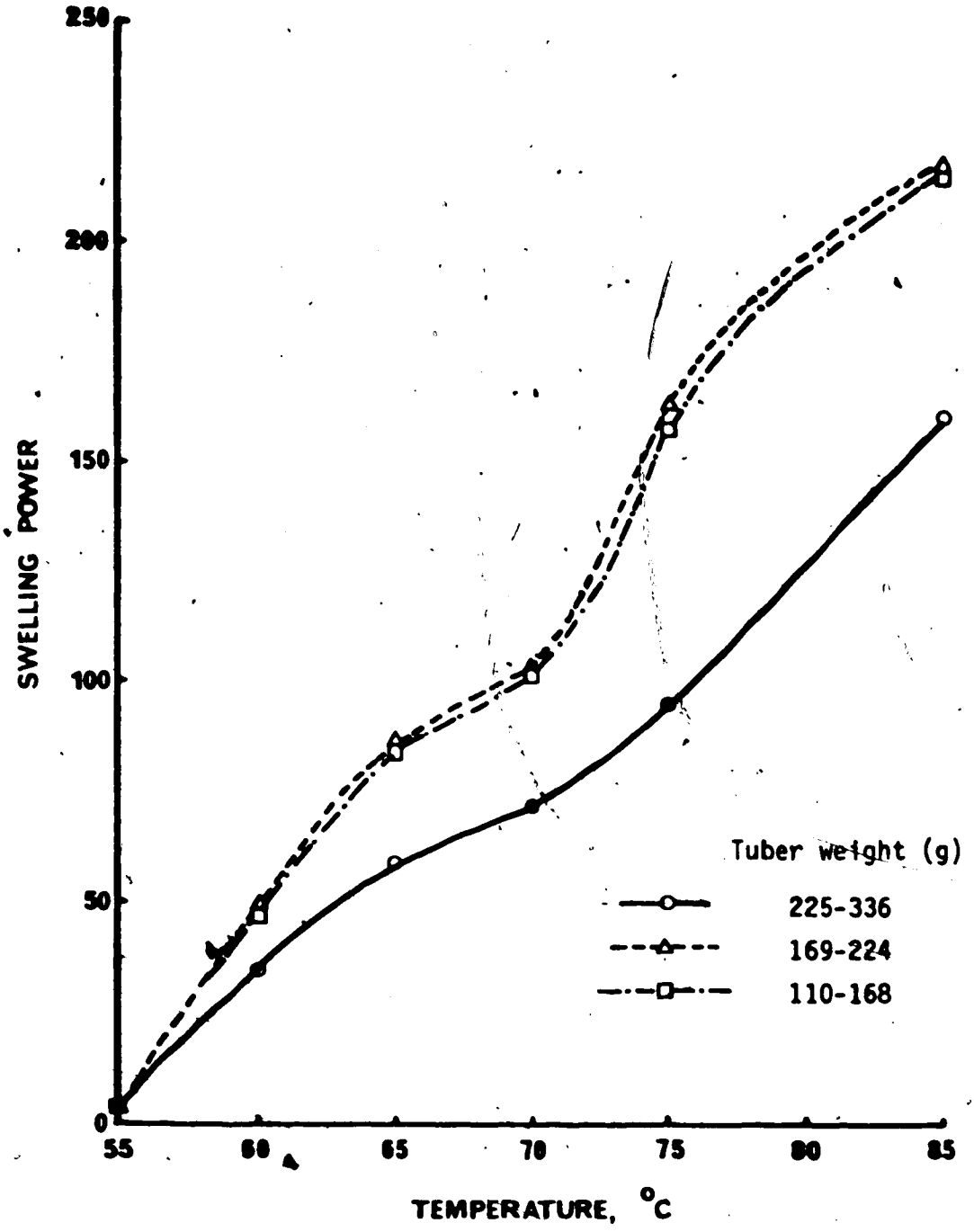

Figure 13. Swelling patterns of starch from Central Alberta potato tubers.

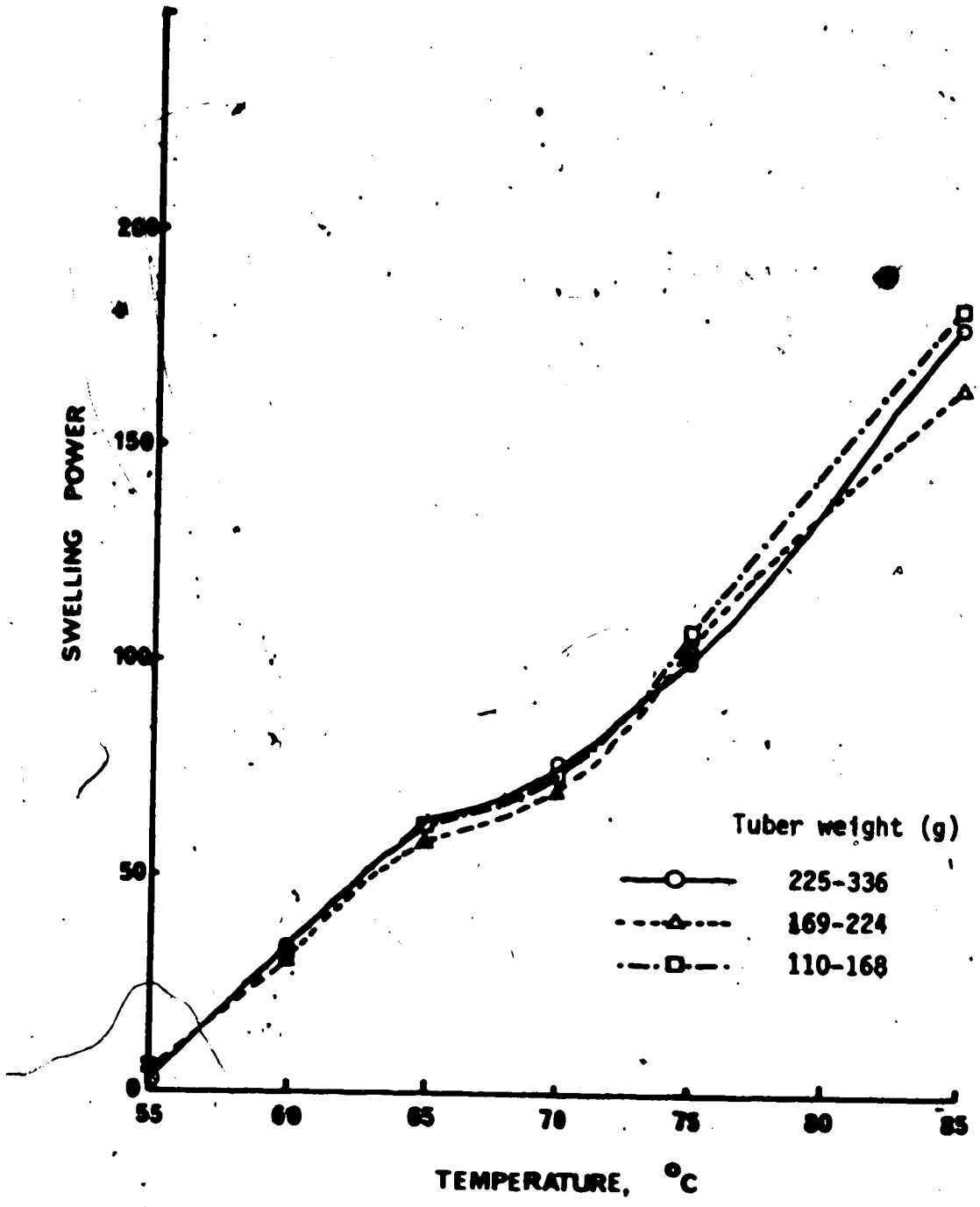

Figure 14. Swelling patterns of starch from Northern Alberta potato tubers.

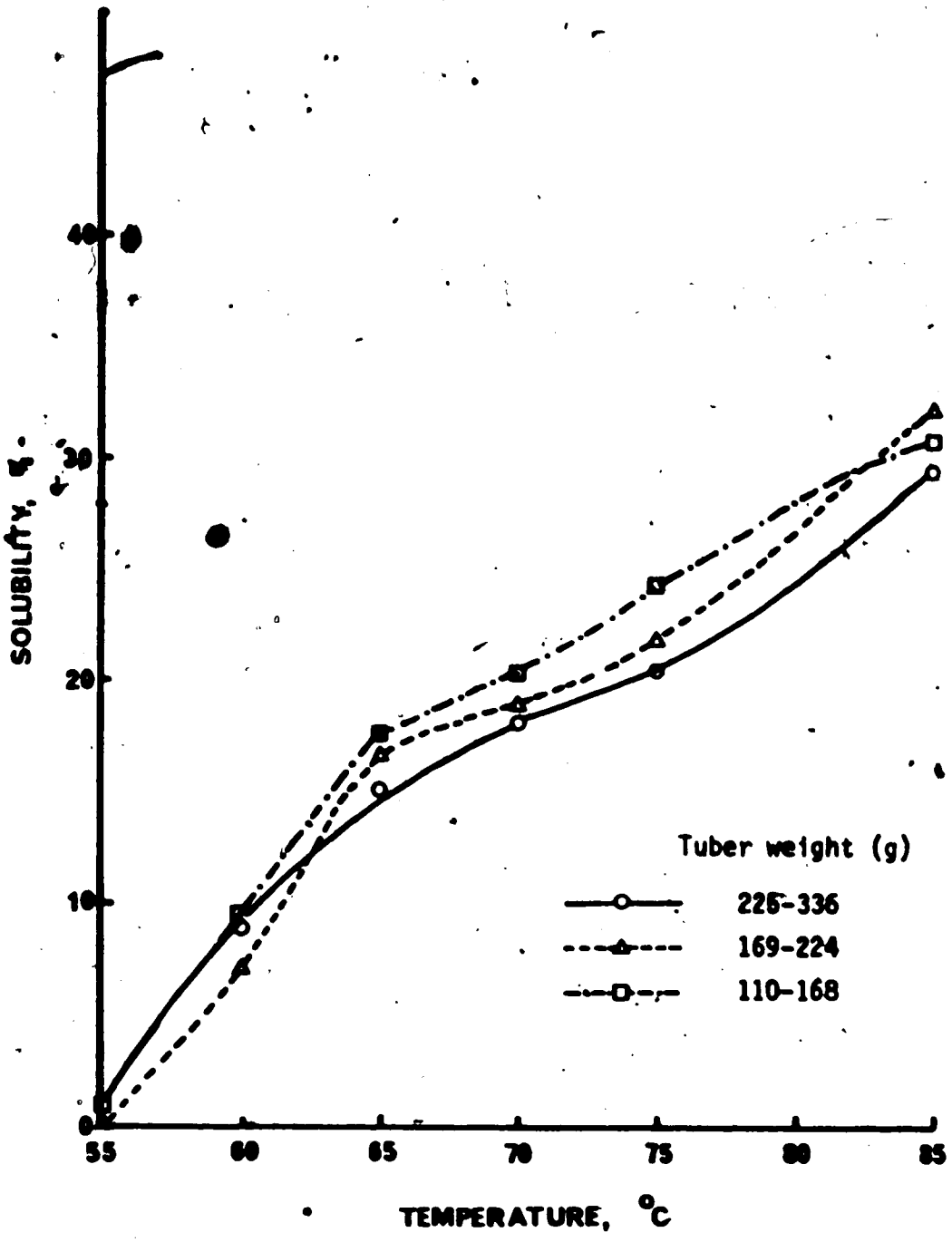

Figure 15. Solubilization patterns of starch from Southern Alberta potato tubers.

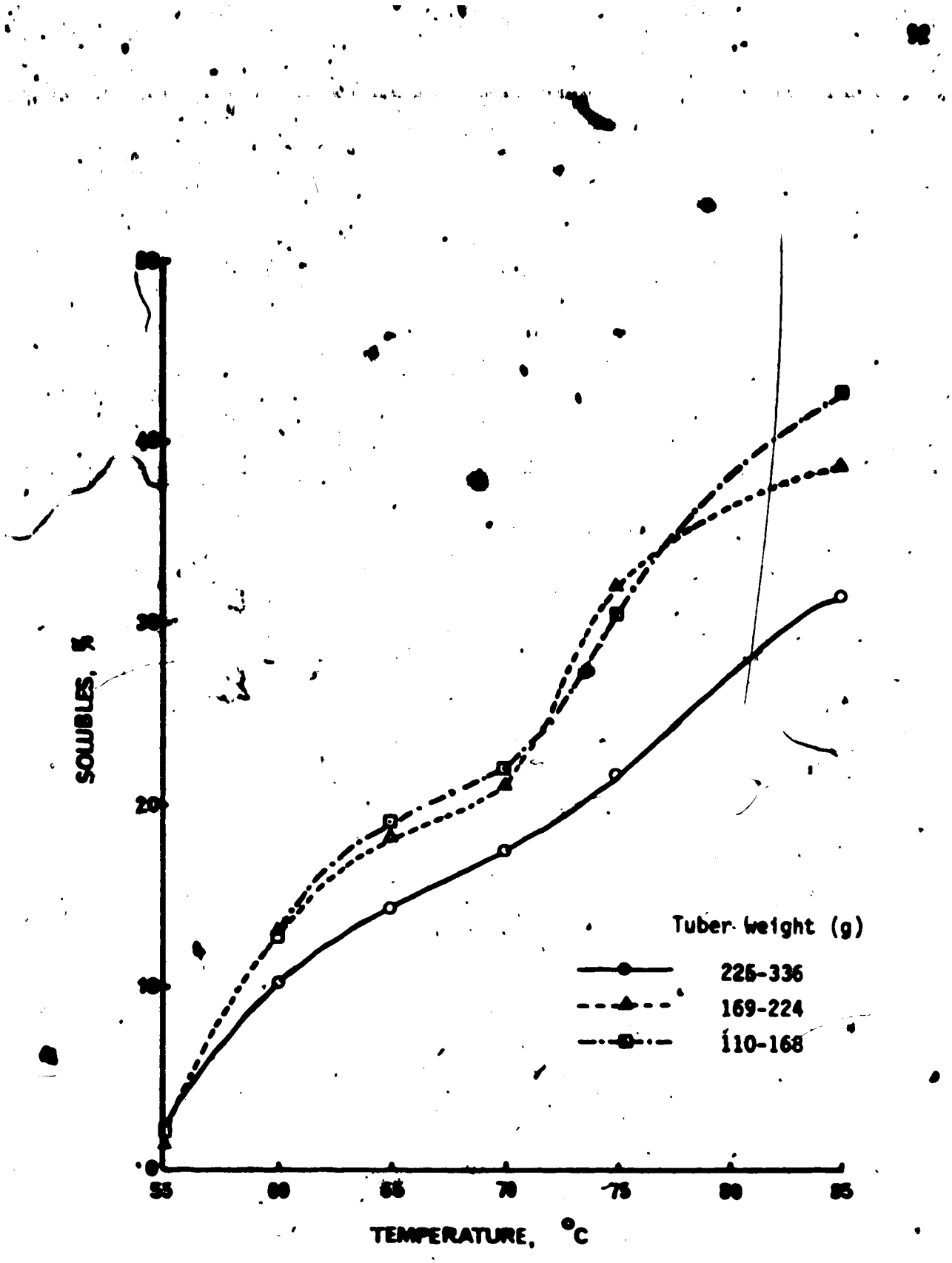

Figure 16. Solubilization patterns of starch from Central Alberta potato tubers.

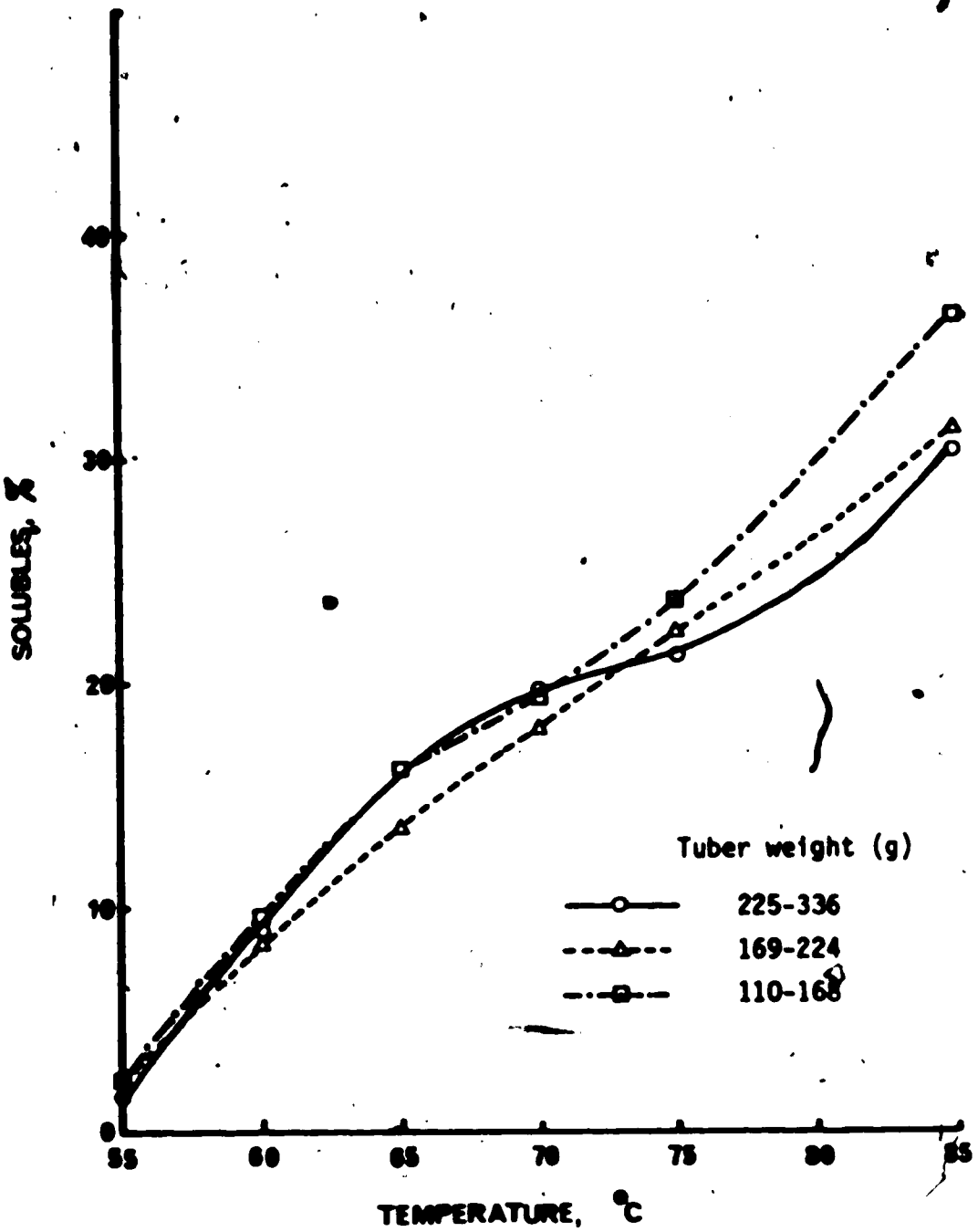

Figure 17. Solubilization patterns of starch from Northern Alberta potato tubers.

grown tubers exhibited the highest SP and solubilization (Figures 13 and 16, respectively). However, when percent solubility of these starches (for 3 tuber sizes) was plotted against SP (Figure 18), the difference ceased to exist. Small variations in swelling and solubilization patterns were found among starch samples from Southern and Northern grown tubers (Figures 12, 14, 15, 17). Figures 19 and 20, illustrating the relationship between percent solubility and SP for these starches, also reveal little difference. Analysis of data from Table 14 shows that the effect of location on starch SP is significant at p=0.01 (Table 4), whereas the effect of tuber size is significant only at p=0.05. Nevertheless, no generalizations could be made about the influence of tuber size, since the effect fluctuated with location.

The high SP observed with the starches from the small and medium sizes of Central Alberta tubers may be attributed to the high starch P content (Table 13), owing to the polyelectrolyte character that the ester phosphate groups impart to the starch molecule (i.e., repulsive forces due to the negative charge in amylopectin molecules). However, the high starch P contents of large sizes of Central Alberta tubers did not parallel their SP values.

The processing quality of potato tubers grown in Alberta was assessed by their suitability for French fries. Frozen French fry quality is dependent on such attributes as flavor, color, oil content, crispness, and mealiness (Isleib

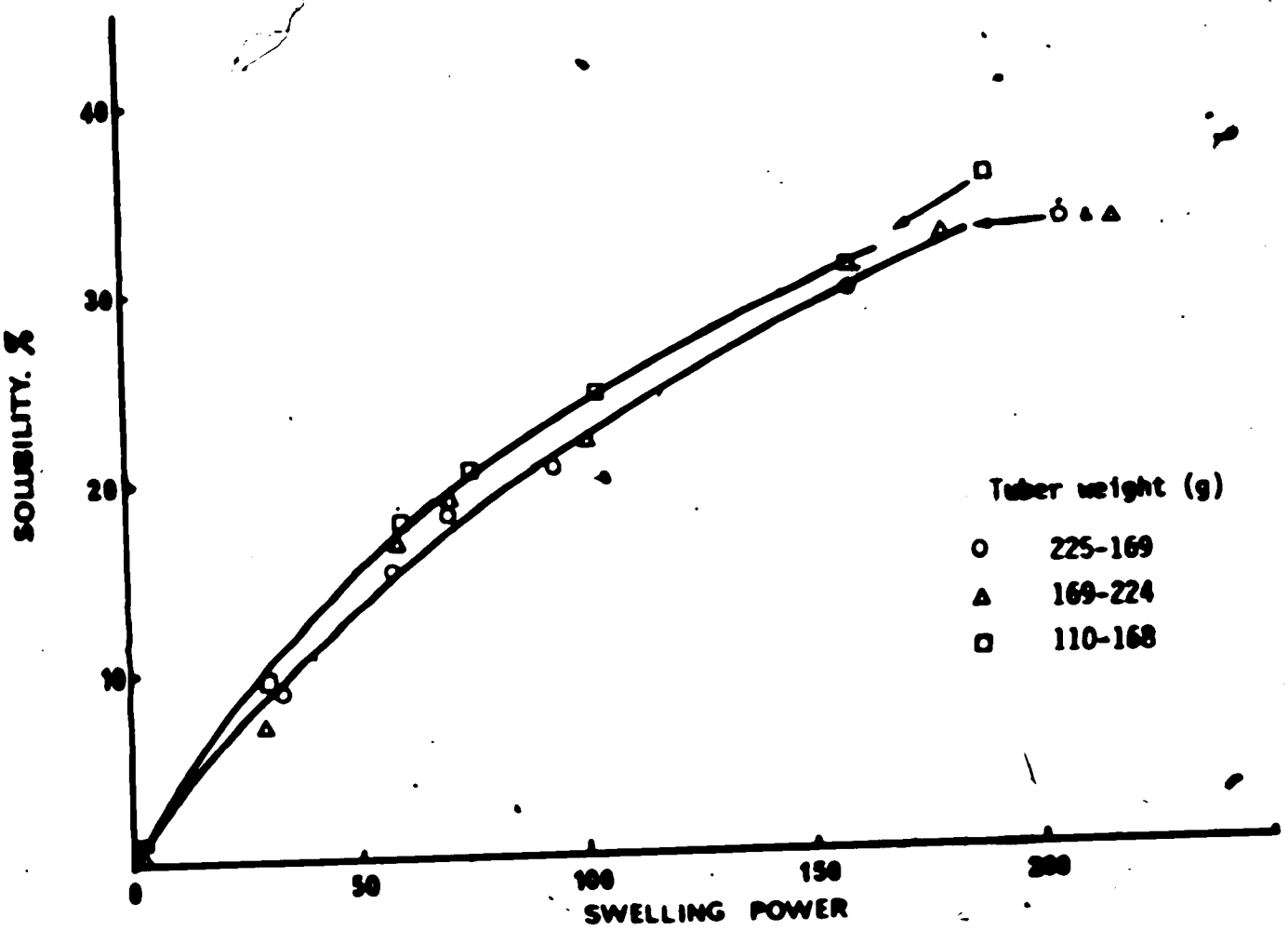

Figure 18. Percent solubility versus swelling power of starches from Southern Alberta potato tubers.

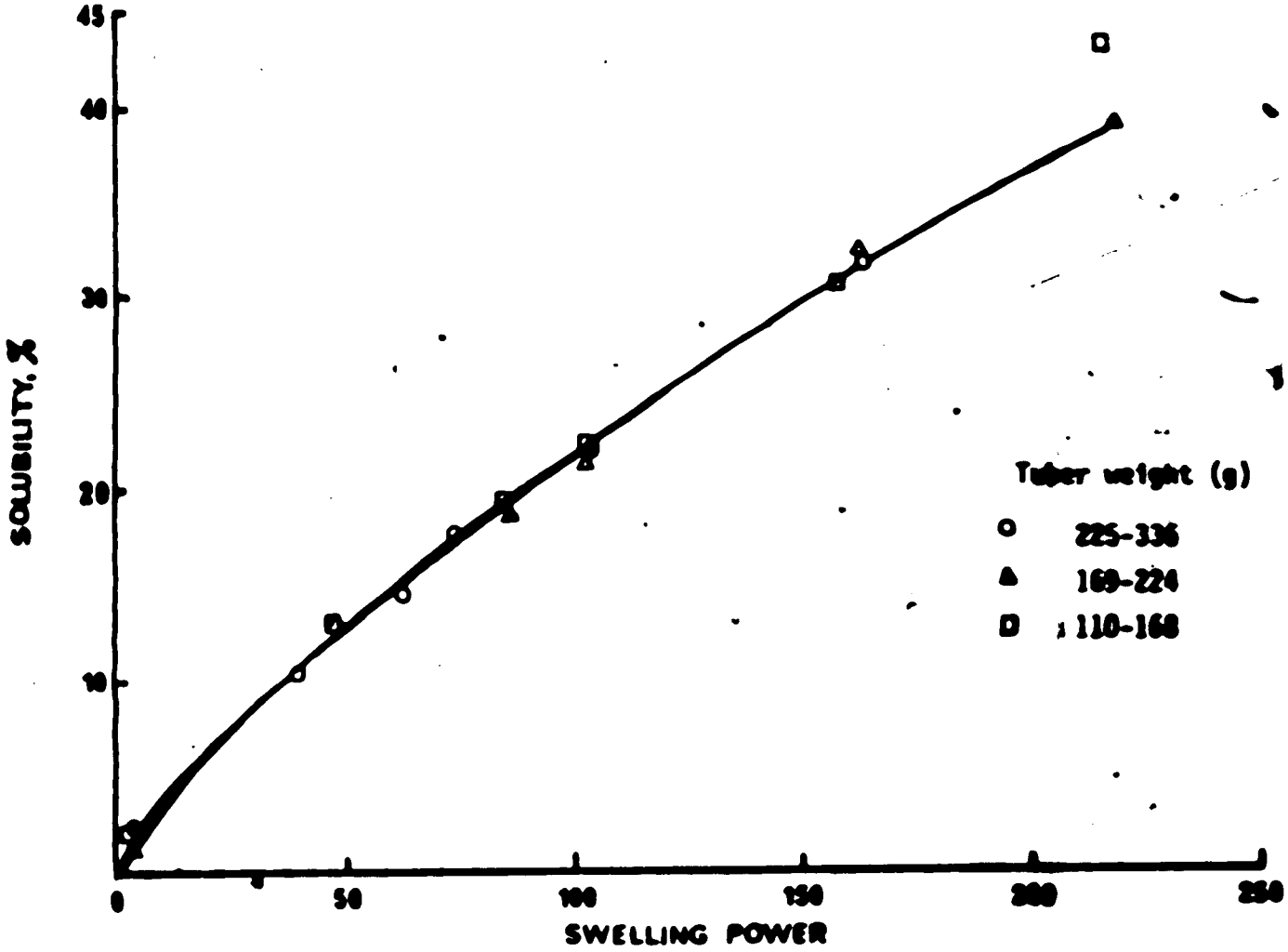

Figure 19. Percent solubility versus swelling power of starches from Central Alberta potato tubers.

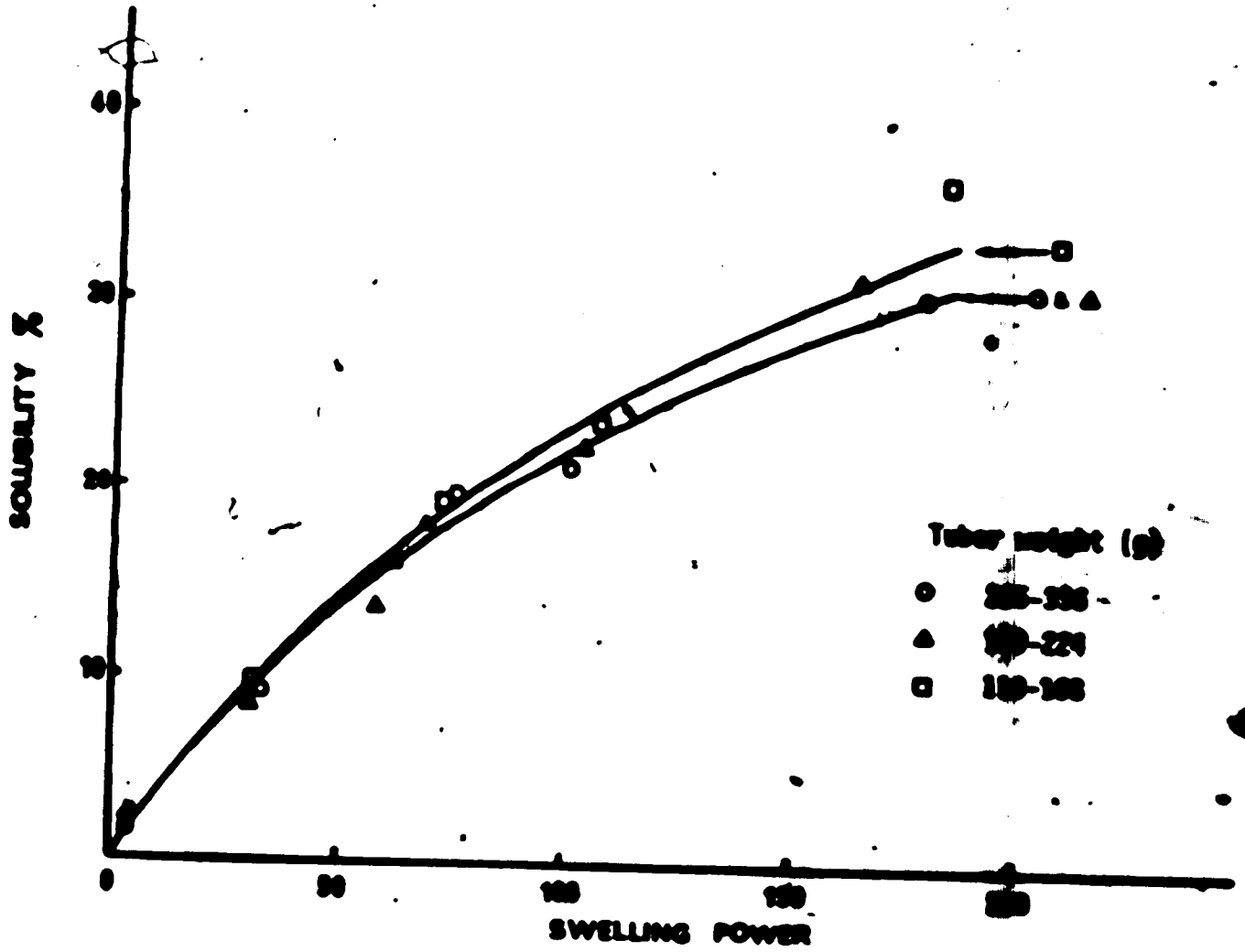

Figure 20. Percent solubility versus swelling power of starches from Northern Alberta potato tubers.

et al., 1964). In the present study, oil uptake served as a quality criterion: the lower the uptake, the better the quality. Also, oil uptake in the end product, aside from affecting its textural quality, represents an economic parameter in industrial-scale French fry production. As seen from Table 10, oil uptake of tuber strips, expressed on a dry weight basis, is significantly influenced by growth location [illegible] while tuber weight [illegible] Based on these data, Southern grown tubers were favored for French fries. The lower oil uptake corresponded with the high DM of these tubers (see Table 8). Thus, the results support the generally accepted opinion of processors that tubers of high DM content usually yield a finished fried product characterized by a favorable low oil uptake.

As indicated earlier, there is no significant difference in the average cell size between tubers on the basis of location (Tables 4, 6-8). Intercellular adhesion, as affected by cell to cell contact, should therefore be of comparable strength in all tubers. The minor variations in the divalent cation contents among tubers and their starch grains (Tables 12 and 13) appear to be rather unlikely to cause a difference in intercellular adhesion. If the claim by Bartolome and Hoff (1972) is valid that increased adhesion can result from bridge formation between the cell wall pectic pectin and divalent cations, particularly those released from starch upon gelatinization. Thus, the high starch content of the tuber, a factor significantly

Table 16. Oil uptake of Target fries prepared from various [illegible] tubers.

Location in Alberta	Tuber wt (g)	Oil uptake (% ppr g DM)
South	110-168	15.32±1.36
	169-224	16.49±1.73
	225-336	15.80±0.72
Central	110-168	19.46±1.69
	169-224	19.77±2.16
	225-336	18.58±1.06
North	110-168	20.17±1.46
	169-224	21.48±2.42
	225-336	20.83±1.19

correlated with sealiness (Barrios et al., 1961b), may have major implications for the processing quality of a tuber in French fry production. The starch content of Southern grown tubers is significantly higher (at p=0.01) than Central and Northern grown tubers. Since the average tuber cell volume does not differ among tubers on the basis of location, it follows that Southern Alberta tubers have, on the average, a higher amount of starch per cell volume. Such tuber tissue was expected to experience enhanced cell separation upon heat treatment in water prior to French frying. As evident from Figure 21b, gelatinization of starch grains within a cell packed with a large number of grains results in the entire cell volume being filled with gelatinized starch. This observation coincides with SEM findings of Fedec et al. (1977), who observed that, while gelatinized starch grains occupy the entire volume of cortical cells, the cells most densely packed with starch grains (see Figure 11a), the perimedullary or pith cell volumes are only partially filled.

Based on the above rationale, it is logical to assume that French fries prepared from Southern Alberta tubers would take up less oil due to less void space being created between gelatinized starch and the cell wall, and also to the ability of gelatinized and retrograded starch to effectively impede oil penetration to cells beneath the strip surface.

In spite of the high starch content of Southern grown

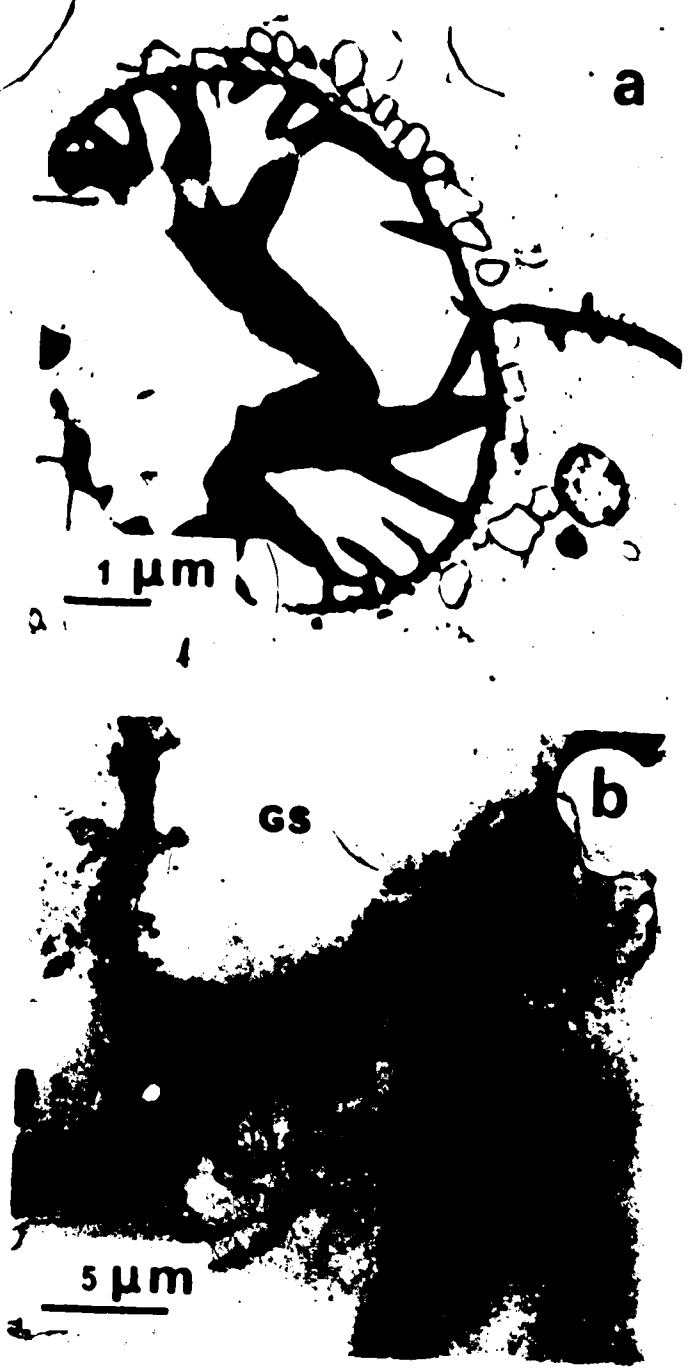

Figure 21. Transmission electron micrographs illustrating:

a. a starch grain surrounded by a double membrane from a raw tuber cortical cell

b. gelatinized starch occupying the entire cortical cell volume in cooked tissue (GS, gelatinized starch; CW, cell wall)

tubers, enhanced cell separation upon cooking is not observed in commercial French fry processing. The present practice, involving precooking of strips at 70°C for 5-8 min, followed by cooling in water and reheating at 70°C for 5-8 min before deep-frying in oil, is then well understood and justified. Precooking at 70°C, based on our findings, should gelatinize all the starch grains within the cell and release the divalent cations of starch which are needed for cell wall firming. Cooling in water should bring about starch retrogradation and assist in cell wall firming. Subsequent heating at 70°C would then not result in sloughing or spontaneous cell separation. As a result of these firming effects imparted to the cell wall, and, particularly, to the middle lamella, tissue cleavage or minute fissure development, which would otherwise provide routes for an additional 10-15% oil uptake, are prevented.

The microscopic investigation carried out by Reeve and Neel (1960) on French fries and chips provides verification of the above claims. The frying process brought about a more rapid dehydration of the gelatinized starch in the surface cells than in the center of the French fry strips. As frying proceeded, expansion of steam entrapped in the cells beneath the strip surface, especially in the intercellular spaces, resulted in localized cell separation (blister formation), as intercellular cohesion became weakened by solubilization of the middle lamella pectic substances between adjacent cell walls. As water escaped in

the form of steam there was movement of oil into the void space that had formed. The authors could not detect the presence of absorbed oil in the strip interior, but did find that the oil was localized mainly in the cellulosic cell walls and intercellular spaces. However, their observation was restricted to French fries prepared without water blanching, when cell separation was not prevented. The oil in French fries prepared with blanching would be localized in the void space within the cell, rather than in the intercellular space, since cell separation would be effectively controlled.

In addition to obtaining basic knowledge of the tuber and starch characteristics with respect to tuber weight and tuber growth location, the present study also included examination of potato starch gelatinization by SEM in an attempt to gain some insight into the ultrastructure of the starch grain. Micrographs illustrating the starch grain morphology at various stages of gelatinization (from 56-70°C) are shown in Figure 22.

The process of starch gelatinization, according to Badenhuizen (1969), involves an initial uptake of water by starch molecules within the grain structure. The uptake is followed by disruption of the molecular organization, being greatest around the hilum. A clear demonstration of this phenomenon is seen in Figure 22b. A cavity results, and it enlarges as swelling proceeds. Starch molecules, mainly amylose, diffuse into the cavity, with fused layers of

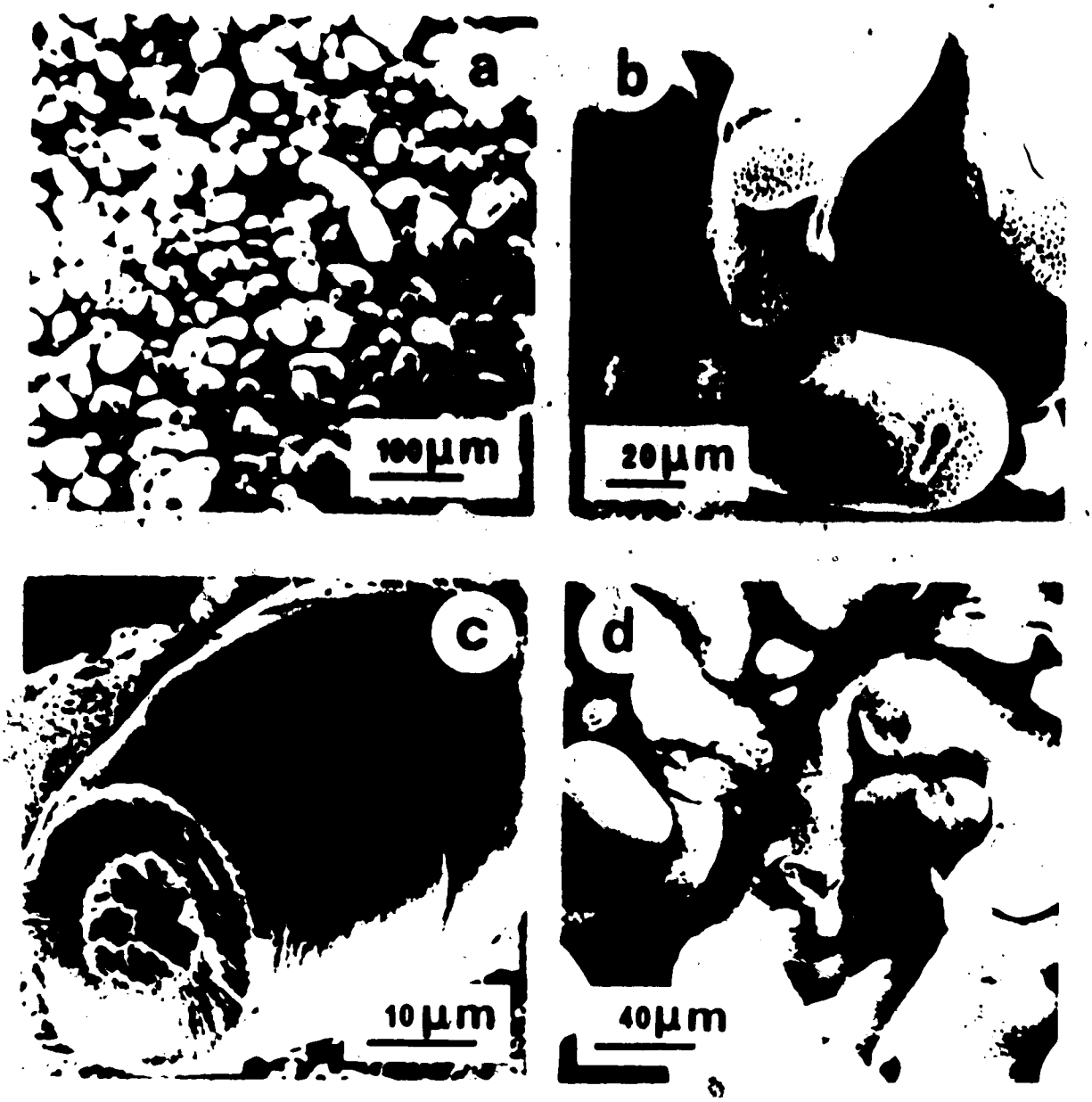

Figure 22. Scanning electron micrographs of native starch grains undergoing gelatinization.

a. control
b. 56°C
c. 56°C
d. 58°C

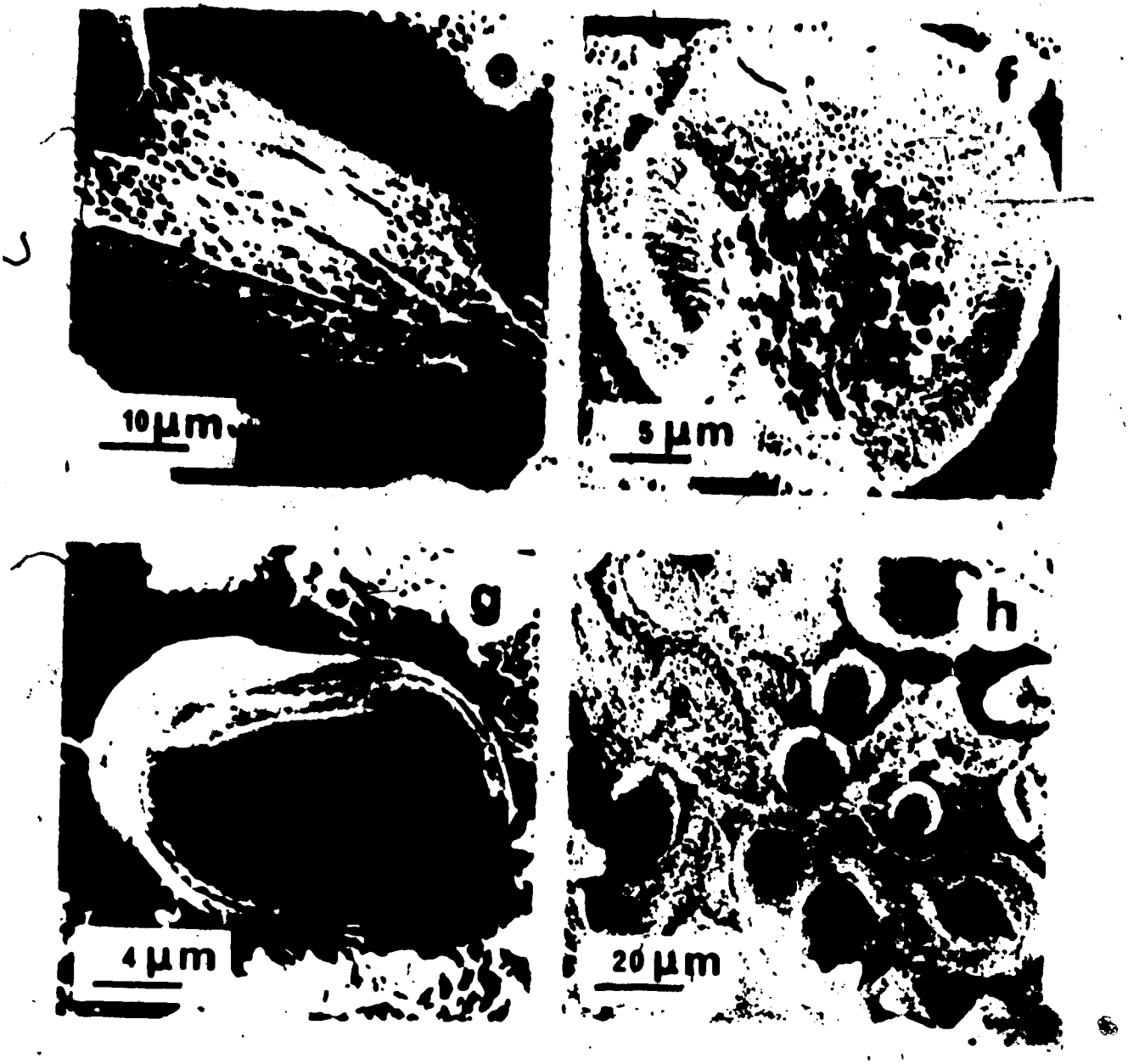

Figure 22. Scanning electron micrographs of native starch grains undergoing gelatinization.

e. 58°C
f. 60°C
g. 60°C
h. 60°C

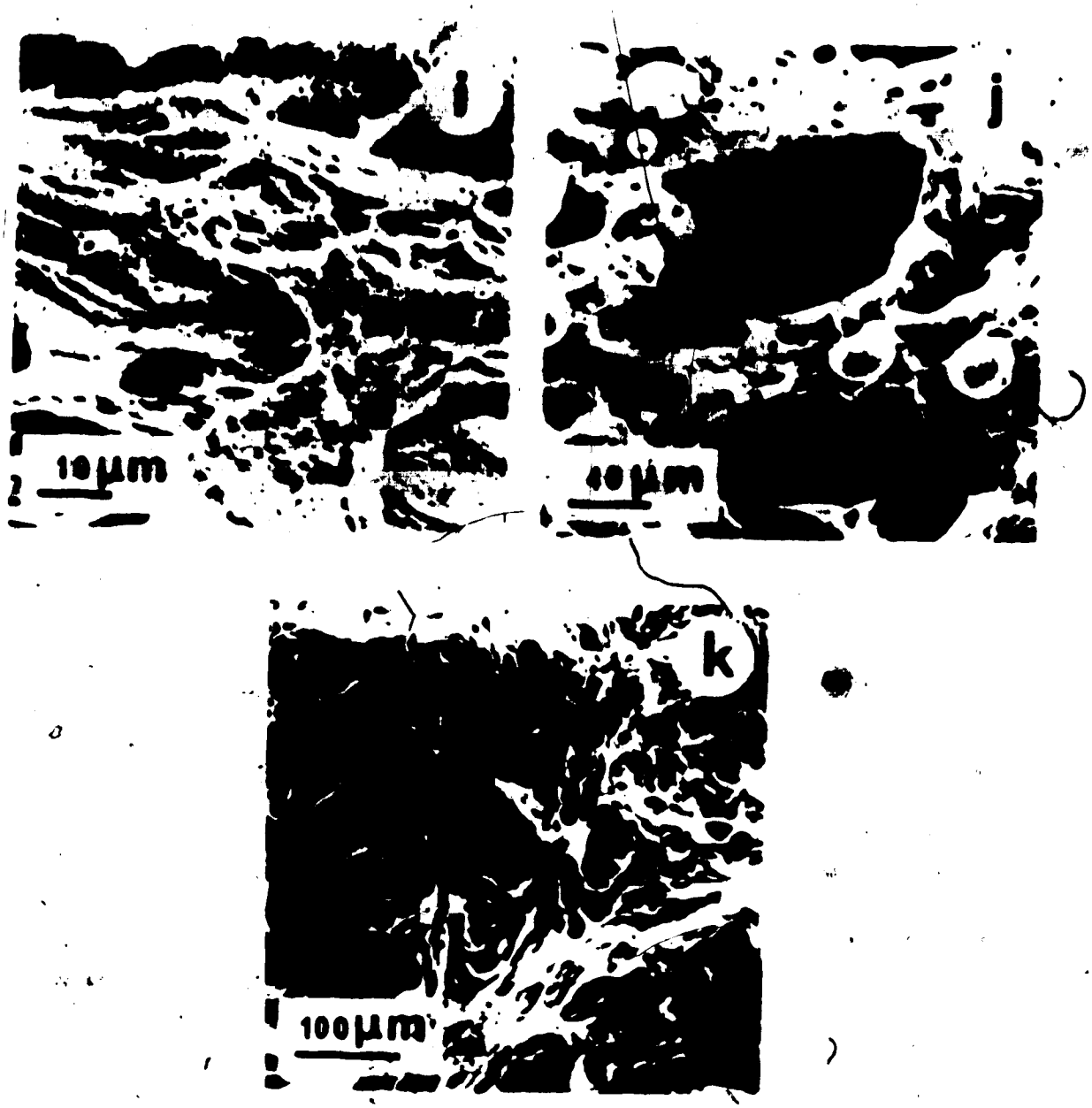

Figure 22. Scanning electron micrographs of native starch grains undergoing gelatinization.

i. 64°C
j. 66°C
k. 70°C

entangled amylopectin molecules surrounding the cavity. Observations of the present study strongly support such a starch gelatinization concept. Development of a cavity in the grain interior is evident in Figure 22e. This is even more pronounced in Figure 22f as the grain undergoes a more advanced stage of gelatinization. The radial fibrillar organization in the wall next to the cavity, which is readily discernible in both figures, is a feature favored by Sterling (1974, 1976) in his starch grain ultrastructure concept. Also of interest were the findings related to the existence of fibrillar structures which traverse longitudinally along the grain surface (Figures 22d,e). The significance of these observations, however, is not yet understood.

Concentric lamellations, readily distinguishable in the fracture face of an intact starch grain, are illustrated in Figure 22g. This structure agrees with the appositional growth of the starch grain as advanced by Badenhuizen and Dutton (1956). Such a lamellar concept was also favored by Gruber et al. (1973), who envisaged the grain ultrastructure as consisting of an amylose core surrounded by layers of crystalline isodiametric micelles of folded amylopectin molecules stabilized in the pleated section of lamellation by intermolecular hydrogen bonding.

Our finding that small starch grains are resistant to gelatinization (Table 8) is confirmed in Figures 22h and 22j. Starch grains of diameters less than 30 μm remain

intact even at 66°C. Complete gelatinization, however, is in evidence at 70°C (Figure 22k).

The gelatinization study provided evidence in support of the existence of both lamellar and radial organization of starch molecules within the potato starch grain.

V. CONCLUSION

Tuber dry matter and starch contents were significantly higher for potatoes grown in Vauxhall compared to those from Winterburn or Peace River. The iodine binding capacity and amylose contents of starches from Vauxhall and Winterburn grown tubers were significantly higher than those from Peace River. Another advantage of Vauxhall potatoes was their significantly lower oil uptake relative to the other two locations. There was no influence of growth location on tissue cell size or starch grain distribution. The largest tuber size, regardless of location, had the largest cell size. On the other hand, there was no significant difference between tuber size as regards tuber dry matter and starch contents, starch grain size distribution within the tuber, oil uptake, and starch iodine binding capacity and amylose content.

As found in this study, tuber size should not be considered as a factor of great importance in decisions pertaining to raw material selection for commercial-scale processing into French fries. Rather, growth location should be accorded greater attention. The causes that bring about such location effects, though not elucidated in this study, are undoubtedly of a complex nature, and are very likely attributable to the interaction of environmental factors and cultural practices.

The present evidence favors Southern over Central or Northern Alberta grown tubers for French fry processing,

since the Southern tubers have high dry matter and starch contents and low oil uptake. However, exact relationships between oil uptake and other tuber and starch variables studied cannot be established. Consequently, it is suggested that dry matter and starch contents be used as guidelines in plant breeding programs intended for upgrading of the processing quality of Central or Northern Alberta grown tubers.

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