GLOBAL CHEESEMAKING TECHNOLOGY

CHEESE QUALITY AND CHARACTERISTICS

EDITED BY
PHOTIS PAPADEMAS
THOMAS BINTSIS

WILEY

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This book is dedicated to our families and to a great teacher, the late Dr R.K. Robinson.

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Preface

The history of cheese goes back to the Neolithic era, parallel to the origins of livestock domestication and dairying, and since then, more than 1000 cheese varieties have evolved. Although cheese is industrially produced in large quantities with a high degree of automation and totally controlled processes, the techniques are very similar to those produced with the traditional methods. Based on the same principles and following basic steps, cheesemakers blend science with 'art', producing a great variety of cheeses.

It is not clear whether cheesemaking is a simple or a complicated process. What is well known is that the impact of a number of different factors in each cheesemaking step is critical, and this is the main reason for the great variability in the characteristics of the final cheese. Thus, the regulation of each factor is vital for producing a cheese with the specific quality characteristics of its variety.

The purpose of this book is to describe (1) the manufacturing process of the most significant cheeses of the world and (2) the quality characteristics of the corresponding individual cheese. In addition, attention is paid to the scientific justification of the development of the final cheese characteristics, and the study of the impact of critical parameters on the development of cheese flavour and texture throughout maturation.

In Part I of the book, some fundamental topics are discussed in order to give a background for a better understanding of cheesemaking and the factors affecting cheese quality. Thus, the history of cheese is presented in Chapter 1; the behaviour of calcium in cheesemilk, during manufacture and during ripening and its impact on the rheological and functional properties of cheese in Chapter 2; cheese flavour development and sensory characteristics in Chapter 3; cheese microbial ecology and safety in Chapter 4; cheese with protected land- and tradition-related labels, traceability and authentication in Chapter 5; an overview of the cheesemaking process in Chapter 6 and traditional wooden equipment used for cheesemaking and their effect on quality in Chapter 7.

In Part II, the cheesemaking processes and the quality and sensory characteristics of 100 cheeses are described. Most of the cheeses presented are traditional products (50 of them with the PDO-Protected Designation of Origin designation). Experts on cheese science and technology gave a comprehensive description of cheese varieties that are important for their country. The cheeses are divided into 13 categories, and each is presented in a separate chapter. Relevant research on each cheese and extensive references to facilitate further studies and stimulate further research on specific aspects of cheesemaking are included.

We wish to express our sincere gratitude to all 43 contributors; for their high professionalism and cooperation.

Photis Papademas and Thomas Bintsis

Part I

1

The History of Cheese

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1.1 Introduction

The International Dairy Federation estimated that global cheese production in 2015 totalled approximately 23 million tonnes (IDF, 2016). This production was spread across six continents and included cheese made mainly from cow (20.7 million tonnes) milk. The remainder is composed of cheese from other species (buffalo, goat and sheep) as well as home-made and farmstead cheeses which do not appear in national statistics. How did this come about? More specifically, where, when and why did cheesemaking begin, how did it spread and evolve, and how did cheese attain such diversity, widespread distribution and prominence in our time? Although our understanding of the history of cheese remains very incomplete, various pieces of this vast puzzle can be fitted together to form a narrative that provides context for global cheesemaking in the twenty-first century.

1.2 Origins of Cheese

Until recently, the origins of cheese have remained mostly shrouded in the impenetrable fog of ancient prehistory. During the past two decades, however, groundbreaking advances in widely ranging fields of research and scholarship have yielded new insights into humanity's earliest experiences with cheese. Indeed, the convergence of multiple trains of research has pushed the likely beginnings of cheesemaking back to the Neolithic, perhaps nearly all the way back to the very origins of livestock domestication and dairying, which provided the context for the emergence of cheese.

Sheep and goats were first domesticated in the upper Euphrates and Tigris River valleys of Southwest Asia, as inferred from the study of archaeological skeletal remains. Advances in techniques to recover, evaluate and statistically analyse skeletal and dental remains for vital diagnostic characteristics such as size, sex and age of the animal at death, along with advances in interpretive frameworks based on ethnographic modelling of management strategies used by semi-nomadic shepherds in Southwest Asia today, have led to breakthroughs in the ability to detect the emergence, and track the spread, of livestock domestication (Vigne, 2011; Vigne & Helmer, 2007). Archaeozoological data clearly demonstrate the occurrence of drastic changes in the slaughtering profiles of sheep and goats, considered indicative of the onset of domestication, around the middle of the 9th millennium BC (Helmer, Gourichon & Vila, 2007; Vigne, 2011; Vigne et al., 2011). Similarly, cattle were also domesticated in the Middle Euphrates basin

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slightly later, again based on archaeozoological analyses (Vigne, 2011). Furthermore, mitochondrial genetic studies of modern sheep, goats and cattle, along with analyses of mitochondrial DNA extracted from Neolithic skeletal remains, also support the conclusion that the earliest domestication of these livestock occurred in the Fertile Crescent region of Southwest Asia (Bollongino et al., 2012; Bonfiglio et al., 2012; Conolly et al., 2012; Edwards et al., 2007; Hiendleder et al., 2002; Meadows et al., 2007; Naderi et al., 2008). Thus, a considerable body of evidence indicates that goat, sheep and cattle domestication occurred for the first time in the same general region of the upper Fertile Crescent, aptly dubbed the 'cradle of agriculture', where the initial domestication of key founder grain crops such as wheat, barley, lentil, pea and chickpea also took place several centuries earlier (Weiss & Zohary, 2011).

It has been widely (though not universally) presumed that domesticated livestock in Southwest Asia were initially raised for their meat, hides and other products resulting from the animals' slaughter, and that the milking of goats, sheep and cattle did not commence until much later, for example, around the 4th millennium BC during the so-called 'secondary products revolution' (Sherratt, 1981, 1983). However, current archaeozoological and archaeochemical findings reveal that dairying was practised much earlier. For example, analyses of dental remains testify to the occurrence of sheep and goat slaughtering profiles, as early as the late 9th millennium BC, that are consistent with milk production (Helmer, Gourichon & Vila, 2007). Dairying practices appear to have then spread rapidly beyond their initial areas of origin, such that by the 8th millennium BC, Neolithic migrants from the northern Levantine mainland had transported domestic sheep and goats to Cyprus, where the animals were raised partly for milk production, as inferred from the early culling profiles observed there (Vigne, 2008; Vigne et al., 2011). Around the same period, archaeozoological remains of domestic cattle in the Northern Levant show similar evidence of culling strategies indicative of milking (Vigne & Helmer, 2007), which eventually spread to central and western Anatolia by the 7th millennium BC (Çakirlar, 2012; Evershed et al., 2008). Thus, ample indirect archaeozoological evidence points to dairying being practised almost from the beginning of the Neolithic when livestock were first domesticated. Indeed, it is not unreasonable to postulate that the harvesting of milk for human consumption may have been among the original reasons that inspired Neolithic farmers to domesticate ruminant livestock in the first place (Vigne, 2008; Vigne & Helmer, 2007).

The first direct evidence for dairying in the archaeological record, however, had to wait until the dawn of pottery making, during the 7th millennium BC. Recent advances in analytical techniques to recover lipid residues preserved within the fabric of ancient unglazed pottery sherds, and to identify the lipid sources based on stable carbon isotope (C^{12} and C^{13}) content, have enabled archaeochemists to reconstruct the contents of many ancient Neolithic pots at the time of their use (Dudd & Evershed, 1998; Mottram et al., 1999). Using this approach, Evershed et al. (2008) demonstrated definitively, and Thissen et al. (2010) corroborated, that milk production occurred as early as the 7th millennium BC in western Anatolia.

This same analytical approach has also made it possible to track the ancient practice of milk production through time and space by analysing pottery remains left behind by migrating Neolithic farmers. For example, a growing body of evidence in the field of archaeoclimatology strongly suggests that a substantial rise in sea level, followed by a major episode of climatic cooling, occurred during the late 7th millennium BC, which in turn precipitated social collapse among Neolithic farmers in Southwest Asia and triggered large-scale migrations out of Southwest Asia into Europe and elsewhere (Clare et al., 2008; Pross et al., 2009; Turney & Brown, 2007; Weninger et al., 2006). Among the evidence for Neolithic migration from Anatolia to Europe around this time are the analyses of potsherds recovered from the Balkan Peninsula that chronicle the spread of dairying as migrating Neolithic farmers transported their pottery-making technology and dairy subsistence strategy with them (Evershed et al., 2008). From there, Neolithic farmers continued their migration into Central, Eastern and Southern Europe by the 6th millennium BC (Craig et al., 2005; Salque et al., 2012; Spangenberg, Jacomet, & Schibler, 2006), the British Isles by the 5th millennium BC (Copley et al., 2003; Copley et al., 2005a,b), and the Western Baltic region, Scandinavia and Finland by the 5th/4th millennium BC (Craig et al., 2011; Cramp et al., 2014; Isaksson & Hallgren, 2012), leaving behind a trail of potsherds containing milk fat residues. Similar analyses have also confirmed the occurrence of dairying as early as the 5th millennium BC in Northern Africa (Dunne et al., 2012), and the 2nd millennium BC in the steppe zone of Central Asia (Outram et al., 2012). Thus, it appears that Neolithic farmers meticulously conserved dairying as a component of their subsistence strategy, even as they migrated vast distances, sometimes under conditions of great environmental stress.

The presence of milk fat residues in ancient potsherds does not necessarily indicate the occurrence of cheesemaking, only that the original pot contained milk in some form at the time of use. However, results from model studies of unglazed potsherds that were exposed to milk products and then buried to simulate conditions of archaeological pottery strongly suggest that the presence of milk fat residues in ancient potsherds constitutes telltale signs of concentrated dairy products such as butter and cheese. For example, unglazed potsherds that were deliberately exposed to liquid full fat milk only absorbed minute levels of milk fat within the pottery fabric, which rapidly degraded to undetectable levels upon burial of the sherds, probably due to microbial breakdown (Copley et al., 2005a; Dudd & Evershed, 1998). Therefore, it seems unlikely that ancient pots that contained only liquid raw milk at the time of use would have retained permanent measurable milk fat residues embedded within the pottery fabric. In contrast, model potsherds that were deliberately dosed with butter and then buried absorbed milk fat into the pottery fabric at 70 times the level observed for liquid milk, and the embedded milk fat underwent much less degradation during burial for up to one year, resulting in the abundant persistence of measurable milk fat residues (Copley et al., 2005a). It is evident, therefore, that concentrated dairy products such as butter and cheese, which contain high levels of milk fat and low levels of water and lactose, are much more likely than liquid milk to transfer abundant milk fat into the fabric of unglazed pottery in a stable form that may persist for immense periods of time under the right conditions; hence, the rationale for the use of milk fat residues as an indicator of concentrated dairy products such as butter or cheese.

Given this context, it is not surprising then, that milk fat residues have also been identified in sherds from Neolithic ceramic sieves recovered from Northeastern and Northwestern Europe, which have been dated to the 6th millennium BC (Salque et al., 2012, 2013). Remnants of Neolithic ceramic sieves have been observed widely in the archaeological material record throughout Central Europe, and similar ceramic sieves from the Bronze Age have been found in Central Italy, the Balkans, and the Indus River region of Pakistan (Barker, 1981; Bogucki, 1984; Gouin, 1997). It has long been suspected that these ancient pottery sieves were used to separate curds from whey during cheesemaking, on the basis of modern peasant ethnography that has documented the widespread use of similar sieves Central Italy, Central Europe, the Balkans and the Middle East (Barker et al., 1991; Gouin, 1997). The findings of Salque et al. (2012, 2013) confirm that Neolithic farmers used such sieves in cheesemaking some 7000 years ago in much the same way as is still practised today in some traditional societies.

In summary, the occurrence of milk fat residues in Neolithic potsherds and sherds, from ceramic sieves in particular, confirms with near certainty that cheesemaking was well under way in Southwest Asia and parts of Europe by the late Neolithic. However, a much earlier origin of cheesemaking, closer to the beginnings of dairying, is also possible. Genetic modelling based on modern human DNA sampling, combined with analyses of DNA recovered from Neolithic human skeletal remains, indicates that humans were universally adult lactose intolerant at the onset of dairying around the 9th millennium BC, due to the ubiquitous downregulation of the lactase enzyme (beta-galactosidase) that occurs after weaning in all mammals (Leonardi et al., 2012). Lacking the lactase production needed to break down lactose in the gut, early Neolithic adults were lactose intolerant, and it took several thousand years from the start of dairying before adult lactase persistence/lactose tolerance became widely established in the human population for the first time in Central Europe, sometime after the 6th millennium BC (Burger et al., 2007; Curry, 2013; Itan et al., 2009; Leonardi et al., 2012). This implies that the earliest harvesting of milk was intended exclusively for young children who were still suckling, to supplement the mothers' milk supply.

However, there is an additional possibility. The processing of milk into lactose-reduced products such as butter, and especially cheese, would have rendered a substantial fraction of the total nutrient portfolio of milk accessible to the Neolithic adult population. Dairying must have provided Neolithic farmers with very strong nutritional advantages for them to conserve milking practices over the many millennia and vast distances of migration that eventually enabled the successful genetic selection for the capacity to express lactase into adulthood. It is not unreasonable to postulate that cheesemaking may have commenced soon after the beginnings of dairying in the early Neolithic, which furnished the new farmers with a powerful nutritional incentive to culturally conserve their dairying practices through the long millennia that ebbed and flowed until adults, too, gained the capacity to benefit directly from consuming milk.

Unfortunately, there is no way to know for certain what Neolithic cheeses were like. Probably they were similar to the simplest cheeses still produced traditionally by semi-nomadic shepherds in Southwest Asia today: fresh, soft, acid coagulated and acid-heat coagulated types, which can be dried in the sun and preserved for later use (Gouin, 1997; Kindstedt, 2012). Alternatively, such types, when heavily salted, lend themselves to packing and preserving in sealed animal skins or clay pots, as is still practised today in Southwest Asia (Kamber, 2008), and which may account for some of the milk fat residues recovered from Neolithic potsherds discussed previously. Whether Neolithic cheesemakers perfected rennet-coagulated cheese is a matter for speculation. The culling of very young male livestock, practised from the beginning of dairying, afforded Neolithic farmers with ample opportunity to observe the milk clotting capacity of animal stomachs. It was only a matter of time before the connection between the clotted contents in the stomachs of the suckling lambs, kids and calves that were routinely culled, and the capacity of the stomach, and its curdled contents, to transform harvested liquid milk into a clotted state, inspired the birth of rennet-coagulated cheese.

From that point on, the basic technologies of acid, acid-heat and especially rennet-coagulated cheesemaking evolved in many different directions as cheesemakers in different places and at different times were confronted with new environmental, ecological, social and economic circumstances that caused them to adapt their practices and equipment to the world in which they found themselves. Great milestones in the circuitous evolution of cheesemaking were marked by the foundational technological advances that we take for granted today, such as the development of techniques and devices for cutting the coagulated mass of milk, for heating the cut mass of curd and whey and for separating whey from curds and applying pressure to the drained mass of curd, all of which facilitated the expulsion of whey from curds; the mastering of salt application levels and techniques; and the commandeering of local natural microenvironments for cheese storage and ripening. Taken collectively, these simple yet profound technical advances elegantly enabled cheesemakers to select for chemical characteristics and microbial populations in their cheeses that rendered positive outcomes that would otherwise be impossible (Kindstedt, 2014). The end result over the course of millennia has been the evolution of the major cheese families, each made up of seemingly endless variations on the family theme.

1.3 Cheese in Antiquity

It was not until several thousand years after start of cheesemaking, however, that descriptive information about cheeses and their manufacture began to be written down as humanity's first civilizations dawned. The earliest known examples of proto-writing, dating from the late 4th millennium BC, come from Uruk, the first great city-state of the Sumerian civilization of Southern Mesopotamia. These proto-cuneiform clay tablets represent the antecedents of humanity's first written language, and among the tablets recovered at Uruk are numerous administrative records that tabulate annual production figures for dairy products, primarily cheese and butteroil (ghee), produced from the milk of state-controlled herds of cattle and flocks of goats and sheep (Englund, 1991, 1995a; Green, 1980). The administrative complexity reflected in these clay records is astonishing and indicates that dairying and dairy processing had become very sophisticated. At the centre of Uruk's economic and political system stood two soaring temples dedicated to Inanna and An, the patron deities of Uruk whose cultic practices demanded a constant supply of agricultural products, including cheese and butter. These cultic practices not only underpinned the religious ideology of Uruk but also formed the basis of its centrally administered redistributive economy (Kindstedt, 2012).

The Inanna mythology of Uruk, and the Inanna-Demuzi cult that it inspired, institutionalised the routine cultic sacrifices of cheese and butter, which were subsequently replicated in various other Sumerian city-states during the 3rd millennium BC. Indeed, more than a thousand years after the initial rise of Uruk, sophisticated administrative oversight of cheese and butteroil production continued to be practised in Sumer, as is evident from abundant cuneiform records recovered from the massive city-state of Ur around the end of the 3rd millennium BC (Englund, 1995b; Gomi 1980). Other written accounts from Ur record the details of daily sacrifices of cheese and butter to Inanna and Ningal (Inanna's mythological mother), always in equal amounts ranging from about 29 to 54 litres of cheese and butteroil per day (Figulla, 1953). This strong linkage between cheese and religious expression is repeatedly observed in the Hittite, Greek and Roman civilizations that followed Sumer, the consequence of powerful currents of cultural influence that flowed northwards and westwards out of Mesopotamia from the Bronze Age forward (Kindstedt, 2012; McCormick, 2012).

Mesopotamia, however, was evidently not the only region where cheese was used as an element of religious expression during the 3rd millennium BC. Craig et al. (2015) uncovered striking evidence of the use of processed dairy products, most likely probably cheese, in religious practices in the vicinity of the Stonehenge megalithic complex in England, dating to around 2500 BC. Their findings, which were based on the identification of milk fat residues embedded in pottery sherds recovered at the site, raise intriguing questions as to whether these religious practices at Stonehenge originated independently of similar concurrent practices in Southern Mesopotamia (approximately 5000 km to the southeast of England), or whether they derived from a common pre-existing religious system that Neolithic migrants from the Levant and Anatolia brought with them to England and Southern Mesopotamia following the great migrations of the 7th millennium BC. Although direct evidence of the use of cheese in religious observances extending back to the 7th millennium BC is lacking, it is interesting to note that ceramic barrel-shaped vessels, believed to be butter churns, have been recovered from a 7th millennium BC Neolithic site in southwest Anatolia that seems to have been a cultic shrine; the churns may have been used for cultic ceremonies (Morris, 2014). Thus, a link between dairy products and religious practices in the early Neolithic seems possible. Unfortunately, detailed analyses of lipid residues in pottery sherds recovered from Neolithic Near East religious sites, which may help to elucidate this mystery, have yet to be reported. Returning to Southern Mesopotamia, a particularly noteworthy feature of Sumerian cuneiform literature from the standpoint of cheese history are modifiers that appear along with the term for cheese, which provide the first descriptive information about cheese in antiquity, and which indicate that cheeses were beginning to diversify. Modifiers that have been translated with reasonable certainty include terms for small and large cheese, herb-flavoured cheese, cheese with cereal grains added, milled or grated cheese, rich cheese, fresh cheese, sharp cheese, white cheese, stinking cheese, and dung cheese (Bottéro, 1985; Stol, 1993). None of these terms provide definitive insight into whether rennet-coagulated cheesemaking was practised in Sumer; however, a few terms have been noted among Sumerian cuneiform texts that could possibly be translated as animal rennet and plant rennet (Stol, 1993).

The first definitive evidence for rennet and rennet-coagulated cheesemaking does not appear in the archaeological record until the rise of the Hittite civilization in Anatolia during the late Bronze Age. Anatolia and Southern Mesopotamia maintained extensive trade networks and cultural exchanges during the Bronze Age; thus, the Hittites were profoundly influenced by Sumerian civilization. For example, they adapted the technique of cuneiform writing to the Hittite language and assimilated many Sumerian cultural features such as architectural forms and religious practices, including the use of cheese in various sacrificial rites (Kindstedt, 2012). Cuneiform texts from the mid-2nd millennia BC reveal that the Hittites performed sacrificial rites involving not only cheese but also rennet, suggesting that rennet had attained a revered status (Güterbock, 1968; Hoffner, 1995, 1998). Other Hittite texts clearly indicate that rennet-coagulated cheesemaking was firmly established in Hittite Anatolia by this time (Wainwright, 1959). Hittite modifiers for cheese that have been translated include terms for small cheese, large cheese, crumbled or grated cheese, scoured or finished cheese, and aged soldier cheese (Carter, 1985; Hoffner, 1966). The latter term suggests that the Hittites used cheese as a military ration, a practice that future armies and navies of Western civilization would often repeat, down to the present.

The Hittite Civilization collapsed around 1200 BC during a period of catastrophic upheaval throughout the Eastern Mediterranean that also triggered an abrupt end to the Greek Mycenaean Civilization, whom Homer referred to as the Achaeans. The cultural legacies of the Mycenaean, Hittite and Sumerian civilizations lived on, however, and helped shape the rise of classical Greek civilization a few hundred years later. The Greek world would come to embrace cheese in daily life and elevate its status to new heights in trade and gastronomic appreciation.

Cheese that the Greeks called 'fresh cheese' was a regular feature of the *opson*, or relish that accompanied the *sitos*, or main course of the Greek meal, which consisted of bread and cereal porridge (Neils, 2008; Wycherley, 1956). Fresh cheese mixed with honey also served as the filling for the beloved flaky cheesecake pastries known as *plakous* or *plakounta*. Fresh cheese probably was a simple rennet-coagulated, uncooked, unpressed or lightly pressed, surface-salted or brine-salted, rennet-coagulated type produced from sheep or goats milk, or blends of the two, much like the fresh white cheeses still produced throughout the Aegean and Eastern Mediterranean regions (Kamber, 2008). The term 'fresh cheese' in Greek literature also refers to the district of the Athens marketplace where cheese was bought and sold, and since every Greek polis (city-state) had a marketplace in the city-centre (agora), each also probably had its own fresh cheese district.

Beyond being common elements of the basic daily Greek meal, cheese and cheesecakes were enjoyed by the aristocracy during the symposium, or drinking party, which was the premier form of entertainment among the upper aristocratic classes (Grandjouan, Markson & Rotroff, 1989; Noussia, 2001). Exceptional local cheeses sometimes became items of maritime commerce, and some cheeses that acquired stellar reputations became identified by their place of origin, such as those from the islands of Cythnos and Chios in the Aegean Sea (Berlin, 1997; Casson, 1954; Migeotte, 2009). Many of the imported cheeses in Athens were probably variants of basic fresh cheese that, when stored and ripened in ceramic jars containing brine, were transformed into the flavourful Feta-type white brined cheeses that became ubiquitous throughout the Aegean and Balkan regions and have remained so to this day (Anifantakis & Moatsou, 2006; Kamber, 2008). Other imported cheeses that were highly esteemed in Athens came from the heavily Greek colonised island of Sicily, where hard, dry cheeses were crafted that were long-lasting yet flavourful enough to serve as condiments in cooking when grated. Sicilian grating cheeses probably consisted of small rennet-coagulated, uncooked, unpressed or lightly pressed, surface-salted sheep and goats milk cheeses similar to those produced in Sardinia and the Southern Italian peninsula today (Kindstedt, 2012). The use of such cheeses in cooking became so popular throughout the Greeks world that Archestratos, a renowned fourth-century BC chef and cookbook writer from Sicily, complained about the overuse of cheese sauces in cooked dishes of the time (Rapp, 1955). Thus, besides serving as a staple of peasant subsistence, cheese in the Greek world became a gourmet luxury food and a flavourful ingredient that added coveted gastronomic variety to an increasingly sophisticated food culture.

The Romans greatly admired Greek culture, and the Greek love of hard, dry pecorino grating cheeses captivated the Romans from the beginning. Indeed, the process began with Etruscans, forerunners of the Romans, whose aristocratic warriors left behind cheese graters, an essential feature of a Homeric feasting ritual that the Etruscans assimilated from the Greeks, in their seventh-century BC tombs (Ridgway, 1997; Sherratt, 2004). By the time of the Roman Empire, the bronze or iron cheese grater had become a standard utensil in the Roman kitchen. The Romans officially recognised two classes of cheese for tax purposes: *caseus mollis*, or soft cheese, and *caseus aridus*, or dry cheese. According to the first-century AD Roman agricultural writer Columella, both cheeses were made from sheep and/or goats milk by a common rennet-coagulated, uncooked, lightly pressed, surfaced-salted make procedure, but to produce the dry version, the salting and pressing steps were repeated, and the pressing pressure was increased (Forster & Heffner, 1954).

Conspicuously absent from Columella's instructional manual on cheesemaking, however, is any mention of one of the most ancient and beloved of cheeses of the Central Italian peninsula, the acid-heat-coagulated (Ricotta) types. The making of whole milk Ricotta seems to have dominated cheese production on the Italian peninsula during the 2nd millennium BC, as inferred from the abundant occurrence of ceramic devices referred to as 'milk boilers' in the archaeological record. Milk boilers, which were produced according to two different designs, were used throughout much of the Italian peninsula during the 2nd millennium BC to prevent heated milk from frothing and boiling over (Potter, 1979; Trump, 1965). Similar devices are still used today by shepherds in the Italian Apennines for the making of traditional Ricotta cheese (Barker, 1981; Barker et al., 1991). Milk boilers disappeared from the Italian archaeological record during the first millennium BC, however, which coincided with the rise of hard pecorino grating cheeses, suggesting that a shift from the making of whole milk Ricotta to whey Ricotta (which is less prone to frothing and boiling over, obviating the need for milk boilers) may have taken place in conjunction with the rise in hard pecorino grating cheese production (Kindstedt, 2012).

The Roman love affair with hard pecorino grating cheeses had not only culinary implications but also military implications as well. The vastness of the Roman Empire, with some 16,000 km of frontier to protect against the 'barbarians' beyond, presented daunting logistical challenges for Roman military planners that had to feed, clothe and otherwise provision a permanent force of nearly half a million soldiers to guard the Empire. To address these needs, Roman forts were endowed with agricultural lands that were used to produce wheat and to raise sheep and pigs for the provisioning of the legions (Bezeczky, 1996; Davies, 1971). Cheese was a basic ration of the Roman military, and the frequent occurrence of perforated heavy-duty ceramic press moulds in the archaeological material records from Roman forts throughout Europe indicate that the making of hard pecorino grating cheese often took place on site, perhaps by the soldiers themselves during times of peace (Davies, 1971; Niblett, Manning & Saunders, 2006). The widespread introduction of Roman cheesemaking technology to Europe north of the Alps left its mark on the future of European cheesemaking, particularly that of the conquering Anglo-Saxons in England, as discussed later.

The Romans were not the first to introduce cheesemaking to Europe north of the Alps, however. On the contrary, they frequently encountered vibrant cheesemaking activities among the Celtic peoples that they conquered, and many cheeses from the provinces to the north came to be imported to Rome, where they attained stellar reputations. Particularly noteworthy were the alpine cheeses that were made all along the arc of the Alps, and the cheeses from the Massif Central of France (Kindstedt, 2012). Thus, the Neolithic migration of dairy farmers from Southwest Asia to Central Europe that occurred thousands of years earlier ultimately gave rise to a very sophisticated and widely dispersed cheesemaking culture in Central Europe by the time of the Roman invasions.

1.4 Cheese in the Middle Ages and Renaissance

Virtually all aspects of medieval life in Europe were profoundly shaped by the two ubiquitous institutions that collectively formed the scaffolding for much of the economic, social, intellectual and spiritual infrastructure of medieval society: the manor and the Benedictine monastery. Cheesemaking in the Middle Ages was no exception. The manor and the monastery were fertile centres of cheesemaking activity, and the great proliferation of new varieties of cheese that came of age during this period is a testimony to the powerful influence that these institutions exercised over cheesemakers.

Because the continent of Europe encompasses extremely diverse physical environments (e.g. with respect to climate, topography, indigenous flora), manorial and monastic cheesemakers were confronted with a wide range of microenvironments, each with its own set of opportunities and constraints, depending on where they were situated. Furthermore, the social and economic structures of manorial and monastic communities differed at different times and in different regions across Europe, which imposed additional formative conditions and constraints on cheesemaking. All of this created incentives for European cheesemakers to develop novel practices and equipment to accommodate their diverse needs. On the other hand, in other regions, cheesemaking technology changed little from the basic methods used throughout the Mediterranean in antiquity. However, the radically different environmental, social and economic conditions of medieval Europe north of the Alps produced very different outcomes even though the same basic Mediterranean technology continued to be employed.

For example, manorial peasant families who made up the labour force of the large manors of Northwest Europe were typically allowed to raise a cow or two on common pastures, which furnished small but vital quantities of milk for the family needs. Peasant wives there employed a basic rennet-coagulated, uncooked, unpressed, surface-salted make procedure, using cow's milk, that was similar to that used by Greek shepherds to produce the ubiquitous 'fresh cheese', and that was used by Italian shepherds to produce the Roman *caseus mollis*, or soft cheese, which Columella described as 'cheese which is to be eaten within a few days while still fresh…' (Forster & Heffner, 1954). Manorial peasant wives probably often had to combine multiple milkings when making cheese because of the small quantity of milk available, which favoured high populations of lactic acid bacteria (and other bacterial species) in the cheesemilk. The end result was the production of small, high-moisture, low-pH (ca. pH 4.6) cheeses. In the warm climate of the Mediterranean, such cheeses spoil or dry out and become inedible within a few days. In the damp temperate climate of Northwest Europe, however, the environmental conditions present in damp cool cellars, or sometimes natural caves, that were used to store the cheeses selected for the prolific growth of surface of yeasts and moulds, especially the greyish-white mould *Penicillium camemberti*, which produced desirable transformations during storage instead of spoilage/rotting. The origins of the plethora of surface mould-ripened (e.g. bloomy rind) cheeses so beloved in Northwest Europe almost certainly had their earliest roots in the peasant manorial communities and, later, the peasant villages that emerged out of the breakup of the manors (Kindstedt, 2012).

In the same regions of Northwest Europe, Benedictine monastic cheesemakers practised the same basic rennet-coagulated, uncooked, unpressed, surface-salted make procedure as their manorial peasant neighbours but arrived at a very different outcome: the evolution of the bacterial smear-ripened cheeses, sometimes referred to as monastery cheeses. Monastic cheesemakers had the advantage of abundant fresh cow's milk from the monastic herd; there was no need to combine multiple milkings for cheesemaking. Warm fresh milk, used immediately after harvesting, ensured low populations of lactic acid bacteria, which resulted in high-moisture cheeses that were higher in initial pH than those of their manorial peasant neighbours. The high moisture, relatively high pH chemistry of the curd, combined with salting techniques that included surface smearing with brine and ready access to cool damp monastic cellars for storage provided the right combination of conditions for prolific yeast and coryneform bacterial growth on the cheese surface that pre-empted spoilage/rotting by transforming the cheese in new desirable ways during storage (Kindstedt, 2014).

In the Southern Massif Central of France, this same basic rennet-coagulated, uncooked, unpressed, surface-salted make procedure gave birth to another radically different cheese, Roquefort, which has become emblematic of the family of blue-veined cheeses. Although cheesemaking in the Roquefort region predated the Romans, it seems that important fine-tuning of the make procedure did not take place until around the eleventh century AD, when manorial sheep ranges and cheesemaking operations on the Larzac Plateau of the Southern Massif Central, and the ageing of cheeses in the famous Caves of Cambalou just below the Plateau, came under monastic control (Whittaker & Goody, 2001). The combination of high-moisture, low-pH sheep milk curd, along with intensive surface salting of the cheese (made possible courtesy of the Romans, who developed salt works along the Mediterranean coast of France and a system of roads ascending from the coast to Massif Central to transport the salt), and access to the Caves of Cambalou for ageing in a well-ventilated, near constant temperature (6–10°C) and humidity (95–98% relative humidity) environment, provided the right combination of conditions for prolific growth of *Penicillium roqueforti* mould growth that produced desirable transformations during storage in place of destructive spoilage/rotting (Kindstedt, 2012). In summary, the simple rennet-coagulated, uncooked, unpressed, surface-salted cheesemaking technology that became deeply embedded in the Mediterranean region in antiquity evolved into radically new families of cheese such as soft surface-ripened types (white mould-ripened and bacterial smear-ripened cheeses) and blue-veined types when practised in diverse European microenvironments.

In England, the conquering Anglo-Saxon aristocracies inherited Roman agricultural infrastructure along with the Roman technology for making small rennet-coagulated, uncooked, lightly pressed surface-salted dry pecorino cheeses of the type described by Columella. Evidently, the Anglo-Saxons continued to produce these small, hard pecorino cheeses on their demesnes for some 500 years until the Normans wrested control of England during the eleventh century AD. With the Normans came the blossoming of trade across the English Channel, including trade in cheeses, which coincided with noteworthy increases in the size of English demesne cheeses, as noted in monastic records of manorial holdings at the time. A change in cheese geometry almost certainly also occurred at this time, as the small cylindrical cheeses of the Anglo-Saxon period evolved into larger wheel-shaped cheeses by the end of the Middle

Ages (Kindstedt, 2012). In other words, English cheesemakers began to modify their practices in response to market opportunities/pressures brought on by trade. Indeed, as the Renaissance dawned and lucrative trade routes re-emerged across Europe after centuries of isolation that followed the collapse of the Roman Empire, cheesemakers in various regions responded to the new world of expanding trade networks with innovative new practices.

For example, cheesemakers in the highlands of Gruyère Switzerland began to produce increasingly larger cheeses during the Renaissance as the reputation of Gruyère cheese grew, and demand in lucrative distant markets soared (Birmingham, 2000). The production of large durable cheeses, which were tailored in size to be transported on foot (in head yokes) over steep mountain passes to Lake Geneva and then packed tightly in barrels for passage down the Rhone River to the Mediterranean, presented immense challenges for the alpine cheesemakers. Moisture control was particularly troublesome because large cheeses possess less surface area relative to their volume than do small cheeses, which slows down evaporative moisture loss outwards from the cheese centre to the surface, and diffusion of salt inwards from the surface to the centre, thereby elevating the risk of spoilage in the high-moisture, low-salt interior during ageing. To combat this, alpine cheesemakers went to great technical lengths to maximise whey expulsion during cheesemaking by cutting the curd into tiny rice-sized particles, cooking the curds to exceptionally high temperatures, and pressing the drained curds into thin wheel-shaped cheeses of immense diameters that maximised the surface area to volume ratio in the finished cheeses. By the end of the Middle Ages, new methods of cooking, pressing and salting developed in various regions of Europe had given birth to a new generation of larger cheeses, ranging from the more diminutive Gouda (ca. 7 kg) in Holland to the massive Parmesan (ca. 40 kg) in the Po River Valley of northern Italy and Cantal (ca. 40 kg) in the northern Massif Central of south-central France (Kindstedt, 2012).

1.5 Cheese in the Modern Era

The seventeenth century arguably marked a turning point in the history of cheese, which ushered in the modern era. The explosive growth of urban populations in rapidly expanding cities such as London, the establishment of truly global trade networks by major European powers as they competed to colonise east and west, and the onset of the Enlightenment, which gave rise to profound scientific advances that soon stimulated the scientific and industrial revolutions, collectively began to change the market forces that confronted modern cheesemakers, as well as the capacity of cheesemakers to respond to market forces with technical innovations. It is true, of course, that market forces affected cheese practices and inspired technical advances long before the seventeenth century, as in the aforementioned example of Gruyère cheese. However, the growing intensity of market forces, which increasingly emphasised efficiency and cost, began to affect cheesemakers in new ways that ultimately paved the way for the cheese factory and industrial cheesemaking.

The beginnings of the modern era are perhaps best illustrated by the transformation that took place in English cheesemaking during the seventeenth and eighteenth centuries, when London became England's foremost population centre. The sprawling metropolis of London created a mega-market that reshaped much of English agriculture, including English cheesemaking. Access to the cheese and butter markets of London was controlled by the London cheesemongers, a cartel of buyers and distributors, who began to apply intense pressure on their suppliers in East Anglia during the early seventeenth century to produce more butter along with their cheese or risk losing their contracts, butter being more profitable to sell in London than cheese. As the demand for butter grew, cheesemakers were forced to skim more cream from their milk before cheesemaking, resulting in cheese with progressively lower fat content. East Anglian cheesemakers lacked the technical expertise to develop high-quality reduced-fat cheeses (a challenge that cheesemakers still wrestle with today), and consequently their product quality deteriorated. The situation reached crisis proportions when the cheesemongers then began to source full fat cheese from Cheshire, effectively forcing East Anglia out of the London cheese market and relegating dairy farmers there to the production of butter. Thus, by the early eighteenth century, East Anglia, which had been London's premier cheese supplier for more than a century, essentially stopped producing cheese, and the Cheshire region became London's foremost supplier (Stern, 1973).

Cheesemakers in Cheshire then quickly came under pressure from the cheesemongers to produce ever-larger cheeses, which were more efficient to transport and distribute, and more profitable because they experienced less moisture loss (and therefore less yield loss) during storage than small cheeses due to their lower surface area relative to volume. However, the move to larger cheeses necessitated innovations in cheesemaking practices and equipment to produce cheese with lower moisture and higher salt contents in the centre that would withstand internal rotting during storage. Cheesemakers in Cheshire responded by phasing in a high-pressure pressing step, using newly developed heavy-duty presses and perforated press moulds, along with a new salting technique that replaced surface salting of the pressed cheese with dry salting of milled curd particles before pressing into cheese (Cheke, 1959; Fussell, 1966). Cheshire cheesemakers then had to develop an alternative protective coating and vapour barrier at the cheese surface to replace the dense rind produced by surface salting, which had previously served as a natural packaging that protected the surface from physical harm and prevented surface cracking. This was accomplished, imperfectly, by smearing inexpensive whey butter on the cheese surface (Kindstedt, 2012).

Despite the impressive, rapid-fire technical innovations developed by the cheesemakers of Cheshire, the region lost its pre-eminence in the London market by the mid-nineteenth century, displaced by cheese produced in the West Country to the south. Cheesemakers there combined a mild cooking or scalding step with the salting of milled curd before high-pressure pressing to render a new cheese variety that eventually came to be called Cheddar. Soon after, English Cheddar cheesemakers found themselves in a technological race for survival as lower-cost Cheddar-style cheese from America, and later Canada, New Zealand and Australia, flooded the London market. Ultimately, the English dairy industry was forced to reorient away from cheesemaking in favour of fresh liquid milk production for the burgeoning urban population of London and other major cities (Blundel & Tregear, 2006). By this time, the modern era of cheesemaking had reached a tipping point, with global market forces and technological innovations firmly in control of the fate of much that would come during the twentieth century and beyond.

Cheesemakers in America, who produced mostly English style cheeses during the seventeenth and eighteenth centuries and who closely emulated the technical innovations coming out of England, rendered this tipping point irreversible during the mid-nineteenth century with the introduction of factory cheesemaking. The factory system, supported by rapid advancements in the field of dairy science and a plethora of new mass-produced labour-saving equipment and utensils, enabled cheese to be made on ever-larger scales with ever-greater efficiency and consistency. By the end of the nineteenth century, the cheese factory had virtually eliminated traditional on-farm artisanal cheesemaking in America while generating astonishing increases in annual US cheese production (Kindstedt, 2012). Highly efficient, large-scale, technology-intense industrial cheesemaking eventually became the norm for many of the world's cheesemaking regions during the twentieth century, including the United States, western Canada, Australia, New Zealand, Ireland, Holland, Denmark and many other regions to varying degrees.

However, a sharp dichotomy also characterised the modern era of cheese from the beginning because many other cheesemaking regions tenaciously continued to produce hand-crafted artisanal cheeses on small scales using traditional practices, even as the factory gained ground elsewhere. Traditional artisanal cheesemaking often persisted in geographically isolated regions of Europe and Southwest Asia, and in regions with marginal lands that are poorly suited for agricultural purposes other than sheep and goat herding. Traditional cheesemaking also persisted in more accessible and fertile regions of Europe and beyond, where strong cultural conservatism prevailed and where traditional cheesemaking formed an integral component of the working landscape, such as in many parts of France and in Quebec, Canada.

As the twentieth century progressed, however, increasingly intense competition from lower-cost industrial cheeses, spurred on by global trade, posed grave challenges to the economic survival of these bastions of traditional cheesemaking. Artisanal cheeses by nature are very labour intensive to produce and not amenable to the cost savings that accompany economies of scale, rendering them much more expensive to the consumer than industrial cheeses (Bouma, Durham & Meunier-Goddik, 2014; Nicholson & Stephenson, 2007). Traditional cheeses also often utilise practices and equipment that conflict with the rapidly evolving global standards for hygiene and safety, posing further threats to their continued existence (Licitra, 2010). Thus, in the twentieth-first century, the long-term sustainability of traditional artisanal cheeses seems unlikely unless (1) modern safety regulations and traditional cheesemaking practices can be reconciled in ways that preserve the essence of traditional cheeses while satisfying the appropriate level of public health protection, and (2) the public can be convinced to pay much more for traditional cheeses than industrial cheeses, either in the form of higher prices or through public subsidies of some sort.

One encouraging model for how this might be accomplished emerged during the past few decades in the United States and several other developed countries, where a new public appreciation for traditional artisanal cheeses has arisen (Kindstedt, 2005). Traditional cheeses collectively offer a rich diversity of intrinsic physical and sensory characteristics that, arguably, are unmatched in industrial cheeses (Licitra, 2010). This diversity, contrasted with the perception of a growing segment of the public that industrial cheeses are bland and uninspiring, has helped to stimulate consumer interest in, and willingness to pay for, a new generation of artisanal cheeses, produced in traditional ways on small scales, but which often employ advanced practices and technologies that satisfy public health regulations while preserving traditional cheese character. Furthermore, the public's willingness to pay more for artisanal cheeses is also being encouraged by extrinsic attributes related to values that consumers hold, such as sustainability and stewardship of the environment, animal welfare, closeness to nature, and so on, which they associate with traditional cheesemaking (Wang et al., 2015). Consequently, small-scale artisanal cheesemakers have at their disposal powerful intrinsic and extrinsic drivers of the public's willingness to pay, which has enabled the new generation of traditional cheesemakers to experience remarkable growth during the last two decades. Effective management of these drivers of consumer willingness to pay, coupled with targeted adoption of technologies to satisfy public health regulations, will undoubtedly be among the keys to future sustainability of traditional cheesemaking worldwide.

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