Aminostratigraphy of Thatcher Basin, SE Idaho: Reassessment of Pleistocene Lakes

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AMINOSTRATIGRAPHY OF THATCHER BASIN, SE IDAHO: REASSESSMENT OF PLEISTOCENE LAKES

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Geology

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

1996
ABSTRACT

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by

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Utah State University, 1996

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The Quaternary geologic history of Lake Thatcher, southeastern Idaho, is pivotal in determining when the Bear River carved its through-flowing channel into the Bonneville Basin. Bright's reconstruction of the history of Lake Thatcher was based on $^{14}$C dates that are now known to be inaccurate. Lava Creek B ash found interbedded with lacustrine sediment suggests that Thatcher Basin contained a lake well before Bright's original estimate of 34 ka.

D/L ratios, which measure the extent of racemization in fossil gastropods, in conjunction with paleosols and tephra, were used to correlate between four localities across Thatcher Basin to reassess lake-level chronology. Lab-heating experiments were performed on four genera of molluscs to obtain intergeneric conversions of D/L, which aided in chronostratigraphic correlation between beds that contained different genera. An age calibration curve for Lymnaea was developed using D/L ratios associated with the proto Mount St. Helens tephra (90 ± 30 ka; D/L = 0.21 [Valvata]) and Lake Bonneville sediment (20 ± 5 ka; D/L = 0.09 [Lymnaea]). D/L ratios from non-dated lake deposits were assigned ages using this calibration curve, providing the basis for the late-Pleistocene Lake
Based on high D/L ratios in *Valvata* (~0.7) contained in the lower Thatcher sediment, lake level through early-middle Pleistocene was shallow, evidenced by numerous paleosols and organic-rich beds. A gap in the Lake Thatcher stratigraphic record exists for much of the middle Pleistocene. Lake Thatcher existed at its highest elevation from ~110 until ~80 ka, separated from the final Lake Thatcher high-water episode at ~40 ka by a middle-Wisconsin soil. This provides a maximum age on the breaching of the divide at Oneida Narrows and unimpeded flow of the Bear River into Bonneville Basin. By ~17 ka, Lake Bonneville backed up into Thatcher Basin, during its all-time highstand, which Bright believed was owed in part to the added inflow of the Bear River. However, evidence from this study suggests that the Bear River may have been spilling over the divide at Oneida Narrows into Bonneville Basin at ~110 ka.
ACKNOWLEDGMENTS

A special thanks to all those who have gone above and beyond the call of duty in providing me with assistance in completing this task. Your genuine kindness, concern, and generosity will be fondly remembered for years to come, a source of light that will forever bring a smile to my face. This project would not have been possible without assistance from: Alan Hochberg, my brother/field assistant, who courageously braved the blazing Idaho sun on my behalf; Caleb Thompson and Paul Vaslet for their field expertise and support; Dave Liddell, Pete Kolesar, and Jim Evans for understanding; Peter Hovingh, mollusc identifier extraordinaire, for his assistance in identifying and collecting molluscs used in this study; Hans and Ruth Mussler and their family for providing me with a trampoline under the stars and an insider's tour of Thatcher Basin; William Nash and Mike Perkins for the time and effort devoted to analyzing and identifying the tephra found in Thatcher Basin; and Andrei Sarna-Wojcicki for his identification of the Proto Mount St. Helens tephra. This project was funded by a grant from Utah State University, obtained by Darrell Kaufman.

Thanks Mom and Dad for your words of wisdom, bits of encouragement, inspirational fossil-collecting excursions, and your love. Thanks for listening, friends and family!

Amy Hochberg
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CHAPTER 1

GEOLOGIC AND GEOGRAPHIC REVIEW OF THATCHER BASIN BASED UPON PREVIOUS WORK

INTRODUCTION

The Quaternary (1.65 million years ago (Ma) to present) was a period of major environmental fluctuations, perhaps more extreme than any other time in the past 60 million years (Bradley, 1985). A detailed record of climate change is necessary for a complete understanding of modern environmental conditions. Quaternary geologists have looked to the oceans, ice sheets, lakes, and the land itself to pinpoint the timings of past climate changes, to understand their magnitude, and to explain the causes behind such drastic fluctuations. This thesis documents fluctuations of lake level in Thatcher Basin, southeastern Idaho (Fig. 1), which can be compared to lake-level fluctuations in other basins in the western United States to identify regional similarities and make paleoclimatic inferences.

Another purpose of this thesis is to determine when the Bear River entered Bonneville Basin. Supplying 40% of the present-day Great Salt Lake surface-water inflow, it has been suggested (Bright, 1963) that the Bear River was partially responsible for Lake Bonneville achieving its greatest highstand 17 thousand years ago (ka). A better understanding of the timing of the entry of the Bear River into the Bonneville Basin is needed to test this proposition. The carving of the divide at Oneida Narrows, which separates Thatcher Basin from the Bonneville Basin, provides a maximum limiting age on the entry of the through-flowing Bear River into the Bonneville Basin. However, evidence from this study suggests that the Bear River may have entered the Bonneville Basin prior to carving the gorge at Oneida Narrows by spilling over the divide upon
Figure 1. Western U.S. showing the Great Basin, Snake River Plain, Yellowstone Hotspot, and major lakes and rivers. Boxed area shown in Figure 2.
reaching its threshold elevation, shedding new light on Bright's original proposition.

This thesis is organized into three chapters. The first presents the geography and previous work on the Late Cenozoic geologic history of Thatcher Basin and the surrounding region. Chapter 2 highlights the principles of amino acid geochronology, the dating method used in this study on molluscs collected from Lake Thatcher sediment, and presents the methods and the results of the amino acid analyses. Results of lab-heating experiments, which allow for comparison of the racemization rates of various molluscan genera, are also provided. Chapter 3 includes stratigraphic columns for four sites that were sampled in Thatcher Basin, providing amino acid data for the molluscs collected. Finally, Thatcher Basin lake-level chronology is interpreted from stratigraphic and amino acid evidence. An age is given for the top of the Lake Thatcher deposits (Main Canyon Formation), providing a maximum age for the breaching of the bedrock divide at Oneida Narrows and consequent entry of the through-flowing Bear River into the Bonneville Basin. And, a proposal was made for the timing of the spillover of Bear River water into the Bonneville Basin, which marks its initial entry, by piecing together the lake-level chronology with basin morphology.

**STUDY AREA GEOGRAPHY**

Thatcher Basin comprises Mound, Gentile, Gem, and Portneuf valleys (Fig. 2). This study focuses on the southern portion of the basin, in Mound and Gentile valleys, which is bounded on the east by the Bear River Range and on the west by the Portneuf Range. Quaternary basalt covers the basin floor in the north, whereas in the south, Quaternary lake deposits prevail (Oriel and Platt, 1983). Lake terraces are the most distinct geomorphic features in the basin. The highest of these reaches 1,660 meters above sea level (m asl) and is visible along portions of the east and west sides of Thatcher
Figure 2. Thatcher Basin, Idaho showing Lake Thatcher (1,660 m asl) and Lake Bonneville (1,555 m asl) shorelines. Boxed area shown in Figure 8. Shaded area is mountainous terrain above ~1,700 m asl.
Basin (Figs. 2 and 3). This terrace is a depositional feature, formed when Lake Thatcher occupied the basin. The lower terrace, at 1,555 m asl, is ascribed to Lake Bonneville and is traceable along portions of both sides of the basin. This terrace formed after Oneida Narrows (Figs. 2 and 4), a bedrock gorge up to 275 m deep and 90 m wide, was cut, connecting Thatcher Basin with Bonneville Basin (Bright, 1963).

The Bear River presently flows through southern Thatcher Basin and into Cache Valley via Oneida Narrows (Fig. 4). The river begins in the Uinta Mountains, flows northward to Soda Point, where it makes a sharp turn southward (Fig. 2) and eventually reaches the Great Salt Lake (Fig. 1). The entire course is approximately 480 km, yet its terminus is only 137 km from its origin (Bright, 1963).

The north rim of Thatcher Basin, in Portneuf Valley near Bancroft (Fig. 2), reaches a maximum elevation of 1698 m, and forms the Great Basin drainage divide (Fig. 1). The topography in this area is formed by Quaternary basalt, suggesting that the drainage divide is unstable and was probably located elsewhere prior to the basaltic volcanism. The Green River is located approximately 120 km to the east of Thatcher Basin and only 100 km from Bear Lake Valley, which is connected to Thatcher Basin via the Bear River (Fig. 1). Geomorphic evidence, fish biogeography, and pebble provenances suggest that the ancestral Green River flowed east out of its basin to join the North Platte River, eventually becoming part of the Mississippi drainage from the early Tertiary until the Quaternary (Hansen, 1985). Fish (cutthroat trout, mountain whitefish, speckled dace, mountain suckers, and sculpins) found in the Green River are believed to have migrated from the Columbia River Basin via the Snake River sometime during the late Pleistocene (Hansen, 1985). The Portneuf River, located 20 km northwest of Bancroft, is part of the Snake River Plain drainage system, which now empties into the Pacific Ocean (Fig. 1). Some molluscan taxa (*Juga, Fontelicella, Gonidea angulata, and*...
Figure 3. Lake Thatcher terrace (1,660 m asl) and Lake Bonneville terrace (1,555 m asl) in Thatcher Basin, Idaho.

Figure 4. View of Oneida Narrows looking south towards Cache Valley, Utah. The Bear River flows north, through the bedrock gorge into Thatcher Basin.
*Pisidium ultramontanum* of Thatcher Basin are of Snake River origin and show that Lake Thatcher was tributary to the Snake River in the early Pleistocene (Taylor and Bright, 1987). Thatcher Basin is, thus, situated in proximity to three major drainage systems. The Bear River presently flows south through Thatcher Basin as part of the Great Basin drainage; however, the drainage divide at the northern end of Thatcher Basin is relatively low and unstable, complicating reconstruction of the drainage history.

**LATE CENOZOIC REGIONAL GEOLOGY**

**The Great Basin**

Thatcher Basin lies in the northeast corner of the Great Basin, an internally drained complex of 150 intermontane basins situated in Nevada, western Utah, and extending into parts of Oregon, California, and Idaho (Fig. 1). About 17 Ma, the Great Basin began to form as the Earth's crust was stretched and thinned to form normal faults that bound the north-trending mountain ranges of the Basin and Range physiographic province (Fiero, 1986; Stokes, 1988).

Thatcher Basin probably existed by the Miocene, when a series of lakes occupied the newly formed basins of the Basin and Range (Stokes, 1988). Wells drilled in the Salt Lake Valley penetrated more than 3,050 m of Pliocene and older Salt Lake Formation (Stokes, 1988). Stokes (1988) suggested that a period of extreme aridity in the Pliocene caused desiccation of the Miocene lakes. However, by late Pliocene to early Pleistocene, Great Basin lakes began filling, and by the late Pleistocene, the Great Basin contained about 120 lakes.

Thatcher Basin contained the northeasternmost embayment of Lake Bonneville, the largest and most intensively studied of the Pleistocene lakes in the Great Basin (Fig. 5). Lake Bonneville was defined by Gilbert (1890) as including all series of Pleistocene
Figure 5. Extent of Lake Bonneville during its most recent highstand ~20 ka. Thatcher Basin formed the northeasternmost embayment of Lake Bonneville.
lake episodes in the basin; his usage of the term will be maintained throughout this thesis. A thorough review of the lake-level history in the Bonneville Basin through ~600 ka has been depicted by McCoy (1987a) (Fig. 6). The oldest known sediments associated with Lake Bonneville contain 2.5 Ma Cudahy Mine, 2.01 Ma Huckleberry Ridge, and 0.74 Ma Bishop tephra layers (Williams, 1994). The deepest onshore exposures of Lake Bonneville deposits are located in a gravel pit in Little Valley, southern Promontory Mountains, Utah (Morrison, 1965). These sediments reach 1,415 m asl and are older than 780 ka (Morrison, 1991). The lake receded below this level before the deposition of the Lava Creek ash (0.62 Ma) and possibly rose shortly thereafter during another lake cycle (McCoy, 1987a). Based on amino acid (D/L) ratios (see Chapter 2) from lacustrine deposits in the Pokes Point Alloformation in Little Valley, the lake rose from below 1,390 to 1,428 m asl 200 ka (McCoy, 1987a). The lake then receded to below 1,385 m asl where it remained for several tens of thousands of years. The sediments of the Little Valley Alloformation were deposited between 130 ka and 150 ka when the lake rose to 1,510 m asl (Scott and others, 1983). The Promontory Geosol, representing tens of thousands of years of paleogenesis, formed in Little Valley deposits during another lowstand near the present level of the Great Salt Lake (1,280 m asl) (McCoy, 1987a). The Cutler Dam Alloformation is the only known evidence for a relatively shallow lake, reaching 1,340 m asl, of probable early-Wisconsin age in the Bonneville Basin (Oviatt and McCoy, 1992). This deposit is older than a non-finite radiocarbon date of >36 ka on wood collected near the base of the alloformation, and D/L ratios in mollusc shells indicate that it is significantly younger than the Little Valley Alloformation.

The history of the last lake cycle in Bonneville Basin is reviewed by Morrison (1991). After 30 ka, Lake Bonneville began to rise. Upon reaching 1,350 m asl, at ~25 ka, the lake flowed into Cache Valley, and after attaining a height of >1,524 m asl at <20
Figure 6. Lake-level fluctuations in the Bonneville Basin during the past 600 ka as depicted by McCoy (1987a).

ka, it entered Thatcher Basin through Oneida Narrows. Lake Bonneville became the largest lake in the Western Hemisphere between 17 and 15 ka, extending 51,700 km² and expanding into northwestern Utah, Nevada, and Idaho (Gilbert, 1890). The lake reached an elevation between 1,551 and 1,585 m asl, forming shorelines at the same elevation in Thatcher Basin (Bright, 1963). At 14.5 ka, Lake Bonneville overtopped its threshold at Red Rock Pass (Fig. 5), causing a catastrophic flood and rapid lowering of Lake Bonneville by 100 m to the Provo level. Lake Bonneville is believed to have stabilized at this elevation for only a few hundred years, after which time climatic conditions caused desiccation, with the lake becoming nearly dry by 11.6 ka. Lake level reached 1,280 m asl, the Gilbert shoreline, by 10.3 ka, receded sometime after 10 ka, and has fluctuated minimally since then.

The lake-level fluctuations of Lake Bonneville, as well as other Pleistocene lakes, were largely climatically induced. Climatic reconstruction is difficult prior to the range of radiocarbon dating (~30 ka) because of limited data and poor resolution of dating.
techniques. However, the abundance of paleoclimate data, such as lake-level fluctuations and vegetation changes, for the late Pleistocene and Holocene allow comparison between localities (see Thompson and others, 1993 for a review of climate changes in the western U.S. since 18 ka). Apparently, at 18 ka the presence of the Laurentide Ice Sheet caused the climate to be cold and dry, yet effectively moister than today in the Great Basin. The colder temperatures and potentially increased cloud cover reduced evaporative loss as evidenced by pollen data from Grays Lake (Beiswenger, 1991) as well as the filling of Lake Bonneville. With the collapse of the ice sheet, beginning after 18 ka, atmospheric circulation was altered, causing the southern branch of the jet stream to migrate northward from its glacial configuration at 30° N to its present position at approximately 50° N. The passage of the jet stream and its associated storm tracks across Lake Bonneville (39° to 42° N) is believed to be responsible for its rapid rise and fall, bringing increased moisture and cloud cover to the areas over which it passed. Lake Bonneville dried by 11.6 ka (Scott and others, 1983) and pollen stratigraphy in southeastern Idaho indicates increased aridity from 10.2 to 10.0 ka (Beiswenger, 1991). Apparently, drastic climatic fluctuations have occurred over a few thousand years, altering the hydrologic budget.

**Yellowstone-Snake River Plain**

While extensional tectonism was commencing in the Great Basin at ~17 Ma, the Yellowstone-Snake River Plain (YSRP) volcanic system was developing in southwestern Idaho, southeastern Oregon, and northern Nevada (Fig. 1) as the North American plate moved across a mantle magmatic source or 'hotspot' (Smith and Braille, 1994). Thatcher Basin is located at the southeastern edge of the Snake River Plain, an 800-km-long by 80-km-wide topographic depression in southern Idaho (Smith and Braille, 1994) that is covered by Late Cenozoic basalt flows and underlain by silicic volcanic rock (Malde,
Although Thatcher Basin is part of the hydrologic Great Basin, it overlaps with the southeastern Snake River Plain physiographic province because it has received basaltic flows and contains eruptive centers associated with Snake River Plain volcanism (Fiesinger and others, 1982). The eastern Snake River Plain contains the greatest accumulation of Quaternary basalts within the western conterminous U.S. (Luedke and Smith, 1991). Unpublished K-Ar dates suggest that the basalt is younger than 1.2 Ma (M. A. Lanphere, U.S. Geological Survey, written communication, 1986 cited in Malde, 1991). Some basalts erupted since 750 ka based on their normal magnetic polarity (Kuntz and others, 1980), whereas several other flows are Holocene based on radiocarbon dating of charred sediment (Kuntz and others, 1986).

The eastern Snake River Plain trends northeastward where it joins the Yellowstone Plateau volcanic field in northwestern Wyoming (Fig. 1) (Luedke and Smith, 1991). The hotspot is presently located somewhere beneath Yellowstone National Park where the youngest rocks of the YSRP volcanic system are found (Smith and Braille, 1994). The heart of Yellowstone National Park, a silicic volcanic field encompassing three giant calderas, is described by Smith and Braille (1994). The first eruption, and the largest, 2.01 Ma, scattered 2,500 km$^3$ of ash, known as Huckleberry Ridge tuff, throughout the western U.S., with an accumulation of at least 3 m in Thatcher Basin. The next caldera-forming eruption occurred at 1.2 Ma, emitting $\sim$280 km$^3$ of Mesa Falls ash, followed at 0.62 Ma by 1,000 km$^3$ of Lava Creek volcanic ash, also found in Thatcher Basin with approximately 2 m of accumulation.

**PREVIOUS WORK IN THATCHER BASIN**

Taylor and Bright (1987) assessed the Late Cenozoic drainage history of Thatcher Basin based on the biogeography of lake molluscs. They suggested that Gentile Valley
drained to the south during the Pliocene, based on the presence of the mollusc *Tryonia* in Lake Thatcher sediments, which is of southern affinity. The date and cause of the truncation of this southward drainage is uncertain, but is believed to have occurred prior to 2 Ma. After this time, Thatcher Basin drained northward, based on the presence of molluscs of Snake River affinity in Thatcher Basin. The distinct molluscan fauna at Bear Lake and Lake Thatcher, which has more extinct, endemic taxa than any other Pliocene-Pleistocene lake basin in the U.S., has been explained by the formation of the Bear River from various other streams in the Quaternary, with Bear Lake having its own internal drainage system prior to that time (Taylor and Bright, 1987).

During the Quaternary, basaltic activity was intense in the areas of Soda Springs and in Gem Valley (Fig. 2) (Luedke and Smith, 1991). Bright (1967) termed the basaltic rocks in Portneuf, Gem, and Gentile valleys the Gem Volcanics. Lava similar in composition to the basalts of the Snake River Plain may have erupted as recently as 30,000 years ago (Luedke and Smith, 1991). Several flows in Gem Valley have K-Ar dates that average ~100 ka (Armstrong and others, 1975). The main source of the basalt flows seems to be on the east side of Portneuf, Gem, and Gentile valleys. Typically, flows range in length from 3 to 16 km and in breadth from 6 to 16 km; larger flows are 2.5 m to 15 m thick, while smaller flows are 0.1 cm to 1.5 m thick. Bright (1963) described two groups of cinder cones in Thatcher Basin; one group is 3 km northwest of Niter and the other is 6 to 8 km north of Grace and 3 km west of Alexander (Fig. 2). The cones are 15 to 45 m high and 100 to 760 m wide at the base and consist mostly of coarse ash and cinders with some bombs over 300 cm in diameter.

The Main Canyon Formation in southern Thatcher Basin is typified by light-colored, horizontal, unconsolidated sediments, predominantly marly silt with minor gravel and sand (Bright, 1963). According to Bright (1963), the sediments of Lake
Bonneville can be distinguished from those of the Main Canyon Formation by color; Bonneville's, which contain Bear River sediments, are red. The red sediment is most concentrated in the clay-size fraction and is likely derived from iron-bearing clastics from Mesozoic sandstone and Tertiary conglomerate south and east of Thatcher Basin. Since he had not identified reddish, Bear River-derived material in the light-colored Thatcher sediment, Bright (1963) proposed that ancestral Bear Lake acted as a sediment trap during Lake Thatcher time.

Bright (1963) claimed that Lake Thatcher owed its existence to the basalts that dammed the north end of Thatcher Basin (Fig. 7). He suggested that ancestral Bear River flowed through the gap at Soda Point to join ancestral Portneuf River at the end of Thatcher Basin where Mabey and Armstrong (1962) inferred a topographic low before it was filled with basalt. More recent work by Mabey (1971), however, suggests that the pre-basalt topographic low is located at the far southern end of Thatcher Basin. According to Bright (1963), the ancestral Portneuf Gorge upstream from Lava Hot Springs was dammed by lava flows sometime prior to 34 ka, causing the Bear River to terminate in Thatcher Basin, forming Lake Thatcher. Based on Bright's (1963) original $^{14}$C dates, which are now known to be erroneous (see below), at approximately 33.5 ka, when the lake reached an elevation of 1,560 m asl, volcanic activity in the basin increased. Basaltic flows divided the basin into two, restricting Lake Thatcher to the southern portion of the basin. By 27 ka, according to Bright (1963), Lake Thatcher rose to its highest level at 1,623 m, spilling over a bedrock divide now cut by Oneida Narrows, permanently diverting the Bear River into the Bonneville Basin. Based on calculations using basin area, and modern evaporation and precipitation rates, Bright (1963) concluded that inflow from the Bear River was necessary to fill Lake Thatcher to its threshold at 1,623. The ancient divide over which Lake Thatcher spilled into Cache
Figure 7. Generalized Lake Thatcher and Lake Bonneville history in Thatcher Basin, Idaho as described by Bright (1963).
Valley was presumably composed of bedrock and the overflow channel is partially preserved as a high-level surface above the gorge (Bright, 1963). The overflowing water would have been shallow and slow moving, taking an appreciable length of time to incise a channel. However, once headward erosion had reduced the length of the sill, the rate of erosion would have increased rapidly. After Lake Thatcher drained, Lake Bonneville began to rise, partly due to the added input of the Bear River.

Bright (1963) reconstructed the origin and development of Lake Thatcher based on radiocarbon dates from Main Canyon Formation sediments that are now known to be inaccurate (Izett, 1981; McCoy, 1987a). Lava Creek B ash in the Main Canyon Formation near Thatcher Church (Fig. 8, Site 3) suggests that the basin contained a lake at least 600 ka and perhaps as long ago as 2 Ma based on the presence of the Huckleberry Ridge ash at the base of the exposure (Izett, 1981). Shells collected stratigraphically between these two tephra have D/L ratios that also suggest that Lake Thatcher was in existence well before Bright's original estimate of 34 ka (McCoy, 1987a). This is consistent with a new K-Ar date of ~600 ka on basalt of the Portneuf Gorge (Scott and others, 1982), which demonstrates that Gem Valley volcanism commenced well before Bright's original 34 ka estimate. D/L ratios measured by McCoy (1987a) in shells from the top of the Main Canyon Formation, at 1,576 m asl in the Main Canyon Dugway (Fig. 8, Site 1), indicate that Lake Thatcher reached its maximum elevation not long before the last rise of Lake Bonneville; perhaps Bright's (1963) radiocarbon date of 27,500 ± 1000 yr B.P. (Lab # W-855) on shells collected from the same site is a not so distant minimum estimate. All of Bright's dates should be considered minimum ages because shells, from which the 14C dates were obtained, are prone to postdepositional isotopic exchange.

Based on D/L ratios measured by McCoy (1987a) and reproduced in this study, the date obtained by Bright (1963) of 32,500 ± 1000 yr B.P. (Lab # W-704) on the lower portion
Figure 8. Thatcher Basin, Idaho showing sample sites. Elevations are in meters above sea level. Shaded areas are mountainous. See Figure 2 for location.
of the Main Canyon Formation near Thatcher Church is hundreds of thousands of years too young.

Bright (Taylor and Bright, 1987) updated his ideas somewhat from his thesis (Bright, 1963) by accepting a new K-Ar age on lava (Scott and others, 1982) that indicated that the northern two thirds of Thatcher Basin were filled with lava during the middle Pleistocene. Taylor and Bright (1987) maintained that Lake Thatcher deepened until it overtopped the divide at about the present site of Oneida Narrows at ~30 ka, or prior, based on radiocarbon dates (Bright, 1967) and D/L ratios (McCoy, 1987a).

Apparently, discrepancies still exist regarding the age of Lake Thatcher, the timing of the breaching of the bedrock divide at Oneida Narrows, and subsequent diversion of the Bear River into the Bonneville Basin. The \(^{14}\text{C}\) dates obtained by Bright (1963) are not substantiated by McCoy's (1987a) amino acid analyses, and in some cases are hundreds of thousands of years too young. The discovery of the Lava Creek B ash interbedded with sediments of the Main Canyon Formation (Izett, 1981) suggests that Lake Thatcher formed at least 620 ka, long before Bright (1963) proposed. The basalt of Portneuf Valley, originally dated at >34 ka (Bright, 1963) and believed to be responsible for the formation of Lake Thatcher, has since been dated at ~600 ka (Scott and others, 1982). Taylor and Bright (1987) loosely placed the breaching of the divide at Oneida Narrows at >30 ka, but the method by which they arrived at this age is unclear.
CHAPTER 2
AMINO ACID GEOCHRONOLOGY: METHODS, INTERGENERIC
CONVERSIONS, AND LIMITATIONS

INTRODUCTION

The principal dating method used in this study is amino acid geochronology performed on molluscs found in Lake Thatcher and Lake Bonneville sediments. Amino acid geochronology is a chemical dating method used for calibrated- and relative-age estimates (see Wehmiller, 1993; Mitterer, 1993 for recent reviews of principles). The shells of living molluscs are formed by the secretion of carbonate on a proteinaceous matrix, composed of approximately 20 amino acids. Upon death of an organism, proteins begin to degrade. The most predictable, and therefore accurate reaction for geochronologic interpretation is racemization. During protein diagenesis, L- (levo) amino acids invert (racemize) to their D- (dextro) isomeric (mirror image) configuration until equilibrium is reached (D/L = 1.0 to 1.3). The proportion of D- to L-forms measures the extent of racemization because no D-amino acids are present when the organism is alive.

The amino acid isoleucine (Ile) is most commonly used in geochronologic investigations because it racemizes slowly, is not a product of decomposition, is not a common contaminant, and because its D-form can be resolved using simple ion-exchange chromatography. L-isoleucine racemizes to D-alloisoleucine (alle); in this study, the ratio of alle to Ile (hereafter, D/L) is used to measure the extent of racemization.

The rate of conversion of L to D is temperature and genus dependent. Results

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1Isoleucine has two centers of assymetry, and inversion of L-isoleucine about the alpha-carbon atom produces the epimer (not a mirror image form) D-alloisoleucine in a process known as epimerization. Epimerization and racemization occur by similar processes; therefore, the general term "racemization" will be used henceforth to include the epimerization reaction.
from lab-heating experiments, in which samples were exposed to known temperatures in a controlled environment, indicate that the rate of racemization doubles for about every 4 °C rise in temperature (Miller and Mangerud, 1985). Also, shells that have experienced larger temperature oscillations have a higher effective diagenetic temperature (EDT) and yield higher racemization rates, despite equivalent mean annual temperatures (MAT) (Miller and Brigham-Grette, 1989). The EDT of a sample is an integration of its thermal history, always higher than the mean temperature it has been exposed to since deposition. The effective temperature at a given depth is a function of the thermal diffusivity of the soil, the temperature range at the soil surface, and the time scale of the temperature cycle (Hillel, 1982). Samples should be collected 2 to 3 m below the surface to minimize the effect of seasonal variation (McCoy, 1987a). Those found in growth position or paired valves minimize the possibility of reworking (Miller and Brigham-Grette, 1989).

Comparison of D/L ratios in shells that have undergone similar diagenetic histories provides a relative chronostratigraphic framework, whereby variation in D/L is interpreted solely as differences in age, a method termed aminostratigraphy (Miller and Hare, 1980). Converting D/L ratios to ages is more problematic. Dated tephra in the study area afford a unique opportunity to calibrate the rate of racemization under local conditions. D/L measured in fossils collected close to independently dated tephra, as well as fossils collected from the last, well-dated Bonneville lake cycle, can be used to develop a dating curve. Calibrated ages (Colman and others, 1987) can then be obtained for an undated sample by interpolation. These age estimates are generally considered more reliable than those derived by estimating the temperature history of a fossil and applying it to an equation that relates fossil age to D/L and temperature (McCoy, 1987b).

In this study, lab-heating experiments were performed on several genera to compare their rates of racemization from the initial to the advanced stages of the reaction.
By heating the shells at elevated temperatures, amino acid diagenesis was simulated for long periods. These data aided in chronostratigraphic correlation between beds that contain different genera. If, for example, Valvata was found at one site, and Sphaerium at another, relative ages could be determined, and correlations could presumably be made by adjusting one D/L ratio to the other based on their difference in racemization rates measured in the laboratory.

METHODS

Fossil Preparation and Analysis

Fossil molluscs were collected at five sites in Thatcher Basin (Fig. 8). In most cases, at least five shells of each genus present were taken from at least 1 m below the present-day land surface. I initially identified the fossils to the genus level using Chamberlin (1929). Peter Hovingh (University of Utah Veteran's Hospital, Salt Lake City) and Robert Hershler (Smithsonian Institution, Washington D.C.) checked and corrected the classification of a subset of shells and provided species-level classifications when known.

Preparation began by placing selected shells into a test tube and assigning them a Utah Amino Acid Laboratory (UAL) number. For each genus collected from a particular bed, at least three preparations were analyzed, labeled A, B, C, and so on. The D/L ratios of the preparations were averaged producing one D/L ratio for the entire sample. Typically only one shell was used for each preparation, unless it weighed less than 5 mg, in which case several were combined. Sphaerium was sampled near the hinge, which is the thickest part of the bivalve shell and most resistant to weathering. The entire shell of the other genera was used, unless oxidization or evidence of bacterial decay existed, in which case only the cleanest part of the shell was sampled. Shells were cleaned
repeatedly in a sonicator for approximately 30 seconds, followed by rinsing with purified water. After all lose debris was removed, the shell was covered with purified water and a few drops of 2N HCl were added. The volume of acid depended upon the mass of the shell. Preparations less than 10 mg were given only one drop of acid (approximately 0.02 ml), and monitored closely, so that the entire shell did not dissolve. More acid was added to larger preparations, with a maximum of five drops for the largest (50 mg). A few preparations were so small (<5 mg) and appeared clean enough that they were not acid leached. When the reaction was complete, or small shells had been leached sufficiently, the preparations were again rinsed several times with purified water and allowed to dry completely in a laminar-flow hood. The preparations were then weighed to the nearest 0.1 mg and transferred to a sterile vial. Using a mechanical pipetor, 7N HCl spiked with norleucine was added in the proportion of 0.02 ml/mg shell. Vials were flushed with N₂, capped, and placed in an oven at 110 °C for 22 hrs. This caused the peptide bonds to break (hydrolyze), so the analysis reveals the total population (acid hydrolysate) of amino acids--the naturally occurring free amino acids plus those bound prior to hydrolysis.

Upon removal from the oven, the preparations were dried under N₂ in a heating block. The preparations were injected into a high performance liquid chromatograph (HPLC) amino acid analyzer produced by Darrell Kaufman and originally designed by Hare and others (1985). Peak heights were used to calculate the D/L ratio. Each preparation was analyzed at least three times, unless the standard deviation of the D/L values between runs was high (coefficient of variation (C.V. = x/σ) > 5%). In this case, another preparation was analyzed until at least three D/L ratios clustered within acceptable limits, or the sample was used up. Throughout this thesis, D/L ratios and standard deviations are reported to the hundredths place and standard deviations <0.01 are reported
as 0.01, commensurate with the accuracy of the amino acid analyzer. In some cases there was strong evidence that the D/L ratio did not accurately represent the age or extent of racemization of the shell based upon results from other shells collected from the same bed, adjacent beds, or heated in the laboratory for the same length of time at the same temperature. Variations in D/L of this sort is the subject of the Sources of Variation section at the end of this chapter. These data were not used to derive equations or to calculate the sample means and standard deviations.

For some shells, the absolute concentrations of ten amino acids were calculated using peak areas calculated by the electronic integrator. Norleucine was added to the preparation in the concentration of 125 pmoles/mg of shell. To calculate the concentration of a particular amino acid, its peak area was divided by the area of the norleucine peak and multiplied by 125 to yield concentrations in pmoles/mg.

Lab-Heated Samples

For the lab-heating experiments, modern Valvata, Amnicola, and Lymnaea were collected, some living and some dead with no soft body attached (Table 1). The dead molluscs proved to be modern by yielding low (<0.02) D/L ratios prior to lab heating. Lymnaea and Sphaerium were collected from lacustrine deposits beside an abandoned channel of the Malad River near Bear River City, Utah and were previously dated at 2420 ± 135 14C yr B.P. (Schaffer-Elder, 1992). Heated preparations of Amnicola and Valvata comprised three to five shells, each shell weighing <2 mg. The Lymnaea and Sphaerium were large enough so that one shell was divided into multiple preparations.

The living molluscs were cleaned by allowing them to dry, cracking their shell, and sonicating. Prior to acid leaching, they were dried under the laminar-flow hood, placed in a glass ampule, covered with 1.12 g of sterilized quartz sand, and moistened
TABLE 1. MOLLUSCS USED IN LAB-HEATING (142° C) EXPERIMENTS

<table>
<thead>
<tr>
<th>Genus</th>
<th>Age</th>
<th>Quad Location</th>
<th>Townships/ranges</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lymnaea</td>
<td>modern</td>
<td>Ogden</td>
<td>Ogden Nature Center NW 1/4 sec. 19, T. 6 N, R. 1 W</td>
<td>This study</td>
</tr>
<tr>
<td>Valvata</td>
<td>modern</td>
<td>Ogden</td>
<td>Ogden Nature Center NW 1/4 sec. 19, T. 6 N, R. 1 W</td>
<td>This study</td>
</tr>
<tr>
<td>Amnicola</td>
<td>modern</td>
<td>Logan</td>
<td>Spring Creek</td>
<td>SE 1/4 sec. 3, T. 11 N, R. 1 E</td>
</tr>
</tbody>
</table>

with 0.224 ml of purified water. The ampules were flame-sealed and placed in a temperature-stable oven for various lengths of time, ranging from 0.5 to 15 days, at ~142 °C. *Amnicola, Valvata,* and *Lymnaea* from Ogden Nature Center comprised lab-heating Set 1. Fossil *Sphaerium* and *Lymnaea* collected from outcrops along the Malad River were prepared several months later and comprised lab-heating Set 2. Fluctuations in oven temperature were noted during this time interval. Because modern shells were used in Set 1 and fossils in Set 2, their results cannot be compared directly. Upon removal from the oven, lab-heated preparations were prepared following standard procedure.

**RESULTS AND DISCUSSION**

The results of the analyses of fossil molluscs collected from Thatcher Basin are discussed in Chapter 3 where they are presented in stratigraphic context. Some fossil data, however, have relevance to the lab-heating results, including D/L ratios from individual stratigraphic beds that contain multiple genera (those used in the lab-heating experiments) (Table 2).
TABLE 2. D/L RATIOS FOR MULTIPLE-GENERA BEDS, THATCHER BASIN

<table>
<thead>
<tr>
<th>UAL #</th>
<th>Site # (Fig. 1)</th>
<th>Genus</th>
<th>Average D/L</th>
<th>σ</th>
<th># Shells</th>
<th>C.V. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1438</td>
<td>4</td>
<td>Lymnaea</td>
<td>0.31</td>
<td>_</td>
<td>1</td>
<td>_</td>
</tr>
<tr>
<td>1439</td>
<td>4</td>
<td>Fluminicola</td>
<td>0.31</td>
<td>0.01</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1440</td>
<td>4</td>
<td>Valvata</td>
<td>0.26</td>
<td>0.03</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>1436, 1437</td>
<td>4</td>
<td>Carinifex</td>
<td>0.25</td>
<td>0.06</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td>1398</td>
<td>4</td>
<td>Fluminicola</td>
<td>0.25</td>
<td>0.02</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>1399, 1400</td>
<td>4</td>
<td>Carinifex</td>
<td>0.23</td>
<td>0.03</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>1397</td>
<td>4</td>
<td>Valvata</td>
<td>0.19</td>
<td>0.03</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>1591</td>
<td>1</td>
<td>Lymnaea</td>
<td>0.11</td>
<td>_</td>
<td>1</td>
<td>_</td>
</tr>
<tr>
<td>1046, 1352</td>
<td>1</td>
<td>Sphaerium</td>
<td>0.18</td>
<td>0.01</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>1590</td>
<td>1</td>
<td>Carinifex</td>
<td>0.15</td>
<td>0.04</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>1047, 1353</td>
<td>1</td>
<td>Fluminicola</td>
<td>0.11</td>
<td>0.03</td>
<td>6</td>
<td>27</td>
</tr>
<tr>
<td>1378</td>
<td>3</td>
<td>Sphaerium</td>
<td>0.57</td>
<td>0.12</td>
<td>2</td>
<td>21</td>
</tr>
<tr>
<td>1379</td>
<td>3</td>
<td>Valvata</td>
<td>0.45</td>
<td>0.13</td>
<td>3</td>
<td>29</td>
</tr>
<tr>
<td>1589</td>
<td>1</td>
<td>Fluminicola</td>
<td>0.26</td>
<td>0.05</td>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>1403, 1587</td>
<td>1</td>
<td>Valvata</td>
<td>0.21</td>
<td>0.04</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>1588</td>
<td>1</td>
<td>Carinifex</td>
<td>0.18</td>
<td>0.02</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>1586</td>
<td>1</td>
<td>Sphaerium</td>
<td>0.28</td>
<td>0.02</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1585</td>
<td>1</td>
<td>Carinifex</td>
<td>0.27</td>
<td>0.03</td>
<td>3</td>
<td>11</td>
</tr>
</tbody>
</table>
Lab-Heated Samples

The lab-heating data (Table 3) for *Lymnaea, Amnicola, Valvata*, and *Sphaerium* demonstrate that the rate of racemization under isothermal conditions at about 142 °C is a nonlinear function of time (Fig. 9). Because racemization is a reversible, first-order reaction (L-amino acid $\rightarrow$ D-amino acid, where $k_1$ and $k_2$ are the forward and reverse rate constants, respectively), its rate under isothermal conditions can be expressed by the equation (Schroeder and Bada, 1976):

$$\text{Time} \propto \ln\left[\frac{1-D/L}{1-0.77*D/L}\right]$$  \hspace{1cm} (1)

This equation assumes that there is no loss or gain of reactants and that the equilibrium constant is 1.3. Graphs of $\ln\left[\frac{1-D/L}{1-0.77*D/L}\right]$ versus time at 142 °C (Fig. 10) show that first-order kinetics is followed up to a D/L value of about 0.7 to 0.8 for *Amnicola, Valvata, Lymnaea*, and *Sphaerium*.

Previous work has demonstrated that isoleucine racemization in fossil molluscs follows reversible first-order kinetics up to D/L of $\sim$0.3 to 0.7, beyond which the reaction slows beyond that predicted by the model (Mitterer and Kriausakul, 1989). This trend is apparent in the results of this study as well (Fig. 10). The trend deviates from first-order because the rate of racemization is dependent upon the position of the amino acid in the peptide chain (Kriausakul and Mitterer, 1978). During the initial stages of protein diagenesis, hydrolytic reactions transfer some isoleucine from the interior of peptide chains to terminal positions where racemization is fastest. As hydrolysis proceeds, the terminally bound amino acids hydrolyze to free amino acids, which racemize slowest, causing the reaction to diverge from first-order reversible kinetics.
**TABLE 3. TIME TABLE FOR LAB-HEATED (142 °C) SAMPLES**

<table>
<thead>
<tr>
<th>UAL #</th>
<th>Genus</th>
<th>Date in oven</th>
<th>Date out of oven</th>
<th>Duration (hr)</th>
<th>D/L</th>
<th>σ*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Set 1 (2/95 - 3/95)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1460A</td>
<td>Lymnaea</td>
<td>–</td>
<td>–</td>
<td>0.0</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>1460B</td>
<td>Lymnaea</td>
<td>–</td>
<td>–</td>
<td>0.0</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>1459A</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/7/95</td>
<td>11.6</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>1458B</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/8/95</td>
<td>35.5</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>1459B</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/8/95</td>
<td>35.5</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>1458C</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/10/95</td>
<td>80.4</td>
<td>0.22</td>
<td>0.01</td>
</tr>
<tr>
<td>1459C</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/10/95</td>
<td>80.4</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>1458D</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/12/95</td>
<td>122.5</td>
<td>0.35</td>
<td>0.01</td>
</tr>
<tr>
<td>1459D</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/12/95</td>
<td>122.5</td>
<td>0.37</td>
<td>0.01</td>
</tr>
<tr>
<td>1499A</td>
<td>Lymnaea</td>
<td>3/30/95</td>
<td>4/4/95</td>
<td>122.5</td>
<td>0.41</td>
<td>0.01</td>
</tr>
<tr>
<td>1458E</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/17/95</td>
<td>240.4</td>
<td>0.52</td>
<td>0.02</td>
</tr>
<tr>
<td>1459E</td>
<td>Lymnaea</td>
<td>2/7/95</td>
<td>2/17/95</td>
<td>240.4</td>
<td>0.71</td>
<td>0.01</td>
</tr>
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* The standard deviation is the analytical error for a single sample solution, the internal reproducibility.
Figure 9. Comparison of isoleucine racemization rates in (a) modern *Amnicola*, *Valvata*, and *Lymnaea* at 142 °C (Set 1) and (b) in fossil *Lymnaea* and *Sphaerium* at 142 °C (Set 2). Data listed in Table 3. Curves are interpolated between data points.
Figure 10. First-order reversible reaction for lab-heated shells at 142 °C Set 1: (a) Amnicola; (b) Lymnaea; (c) Valvata; and Set 2: (d) Lymnaea; and (e) Sphaerium. Least-squares regressions based solely upon data that follow first-order linear kinetics.
Intergeneric Comparison of 
Racemization Rates

Wehmiller (1980) suggested that intergeneric variation in racemization rates results from genus-dependent rates of protein hydrolysis, which in turn influences the rate of racemization. The rate of hydrolysis depends on the taxon-dependent sequence of amino acids in a peptide or protein. Generally, the higher the concentration of aspartic acid and other amino acids that form stable peptide bonds, the lower the rate of hydrolysis and, therefore, the lower the rate of racemization.

I compared the rate constants (k = slope of regression line in Fig. 10) for the different genera at 142 °C to determine their relative rates of racemization. I also compared the lab-heating results with the relative rates of racemization (D/L ratios) measured in different genera from the same stratigraphic horizon.

*Lymnaea* /Amnicola. The 95% confidence intervals about k (Table 4) indicate that the rates of racemization in *Lymnaea* and *Amnicola* are distinguishable and that *Amnicola* racemizes at a significantly higher rate than *Lymnaea*. This trend is also seen in the D/L data from the fossil snails. To determine how closely lab-heating experiments mimic natural diagenetic processes, the lab-heating data for *Lymnaea* and *Amnicola* (Table 3) were compared to fossil *Lymnaea* and *Amnicola*, the most common genera reported in the literature and found in the Great Basin (Table 5). *Amnicola* consistently racemizes faster than *Lymnaea*; in 29 out of 30 beds, *Amnicola* yields a higher D/L ratio than *Lymnaea*. The D/L ratios in fossil *Lymnaea* and *Amnicola* collected from the same bed were plotted with D/L ratios measured in lab-heated shells; average values were calculated in the case of duplicate samples (Fig. 11). The data overlap, suggesting that the lab-heating experiment (142 °C) simulates natural diagenetic processes.

An equation was formulated based upon the two data sets using a reduced major-
axis line described by Till (1974) for quantifying the relationship between two variables, neither of which is dependent or known without error. The two long-duration heated samples were not used to calculate the relationship because they are beyond the range of D/L ratios measured in fossils from Thatcher Basin and because their distance from the centroid of the data set strongly influences the slope of the major-axis line. The equation that can be used to convert D/L measured in *Lymnaea* to D/L *Amnicola* is:

\[ Y = 1.284X + 0.007 \] (2)

where X is D/L in *Lymnaea* and Y is D/L in *Amnicola*. This indicates that *Amnicola* racemizes 28% faster than *Lymnaea*.

**Comparison Between Other Genera.** In contrast to the consistent offset in D/L measured in *Amnicola/Lymnaea* fossil and lab-heated pairs, the relative rates of racemization measured for other genera pairs is more variable. The 95% confidence intervals around k for *Valvata* overlaps with that of *Lymnaea* and *Amnicola* for lab-heated Set 1, and k for *Lymnaea* and *Sphaerium* for lab-heated Set 2 also overlap at 95%, suggesting that the rates of racemization for these pairs of genera are indistinguishable.
TABLE 5. PREVIOUSLY PUBLISHED D/L RATIOS MEASURED IN FOSSIL SHELLS OF DIFFERENT GENERA OF THE SAME AGE

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<th>Sphaerium D/L</th>
<th>Valvata D/L</th>
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<td>McCoy (1987a)</td>
</tr>
<tr>
<td>AAL 1281</td>
<td>0.14</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td>Thatcher Basin</td>
<td>McCoy (1987a)</td>
</tr>
<tr>
<td>AAL 1282</td>
<td>0.19</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
<td>Thatcher Basin</td>
<td>McCoy (1987a)</td>
</tr>
<tr>
<td>AAL 889, 853, 888</td>
<td>0.38</td>
<td>0.55</td>
<td>0.49</td>
<td></td>
<td></td>
<td>Searles Lake</td>
<td>Miller and Hare (1980)</td>
</tr>
<tr>
<td>AAL 1456, 1458</td>
<td>0.14</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td>Bonneville Basin</td>
<td>Oviatt (1991b)</td>
</tr>
<tr>
<td>AAL 1446, 1447</td>
<td>0.14</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td>Bonneville Basin</td>
<td>Oviatt (1992)</td>
</tr>
</tbody>
</table>

* Samples prepared and analyzed in 1980 when all D/L ratios were consistently high (McCoy, 1987a).
Figure 11. (a) Relationship between D/L ratios measured in coeval fossil *Lymnaea* and *Amnicola* (Table 5) and *Lymnaea* and *Amnicola* heated simultaneously at 142 °C (Table 3). Comparison of the extent of isoleucine racemization in lab-heated (b) *Lymnaea* and *Valvata*; (c) *Amnicola* and *Valvata*; and (d) *Lymnaea* and *Sphaerium*.
(Table 4). If the lab-heated data do not completely conform to the first-order kinetic model, however, k may not accurately represent the rate constants for the genera, which may explain the lack of distinction.

As an alternative assessment of the relative rates of racemization observed in the lab-heated shells, D/L ratios measured in shells subjected to the same duration of heating were compared directly to one another (Fig. 11). The average percent difference between the D/L ratios of heated pairs was calculated for shells with D/L ratios in the range of interest (0.05 to 0.55). Using this approach, *Amnicola* racemizes about 21% faster than *Valvata*; *Valvata* racemizes about 17% faster than *Lymnaea*; and *Sphaerium* racemizes about 26% faster than *Lymnaea* (Table 6). This assessment appears to suggest that there are consistent differences between the rates of racemization in these genera.

### TABLE 6. DIFFERENCE IN THE RATES OF RACEMIZATION FOR LAB-HEATED SAMPLES (142 °C)

<table>
<thead>
<tr>
<th>Shell pair</th>
<th>% difference</th>
<th>σ</th>
<th>n (# pairs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Amnicola</em></td>
<td>Valvata</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td><em>Valvata</em></td>
<td><em>Lymnaea</em></td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td><em>Sphaerium</em></td>
<td><em>Lymnaea</em></td>
<td>26</td>
<td>39</td>
</tr>
</tbody>
</table>
Unlike the relatively consistent offset in D/L measured in simultaneously heated genera pairs, D/L ratios in coeval fossil pairs generally do not show consistent differences (Tables 2 and 5). This may be because significantly fewer fossil data are available for the other genera, making trends less obvious, or because their relative rates of racemization are similar. Of the five fossil Lymnaea/Valvata pairs, three Lymnaea have higher D/L ratios. In two of the four Valvata/Sphaerium pairs, Sphaerium has a higher D/L ratio, and one pair has indistinguishable ratios. Three out of four fossil Valvata/Amnicola pairs show Amnicola yielding higher D/L ratios. Sphaerium racemizes 64% faster than Lymnaea in the one fossil Sphaerium/Lymnaea pair. Whether the differences in rates of racemization between genera observed in the lab-heating data mimic the results from fossil Lymnaea/Valvata, Valvata/Amnicola, and Sphaerium/Lymnaea pairs is unclear; more data are needed for an accurate assessment. Apparently, the lab-heating experiments suggest consistent differences that are not entirely supported by the D/L ratios measured in fossils of some genera.

Although there are no lab-heating results for comparison, the D/L ratios in the three Carinifex/Valvata pairs from Thatcher Basin fossil data overlap at ±1σ (Table 2). Similarly, the D/L ratios measured in one pair of McCoy's (1987a) Carinifex/Valvata differ by only 0.01 suggesting that there is no difference in the rates of racemization between these genera. In three out of four beds in Thatcher Basin, Fluminicola has a higher D/L ratio than Carinifex, with overlap of the D/L ratios at ±1σ in three of the four beds, suggesting that, based on minimal fossil data, Fluminicola racemizes faster than Carinifex. Fluminicola also racemizes faster than Valvata in all three fossil beds that contain both genera, with overlap of the D/L ratios at ±1σ in only one bed. In the six multi-genera beds in which Sphaerium is present, it has the highest D/L ratio in four beds.
Overall, *Amnicola* consistently has the highest rate of racemization, and *Lymnaea* the lowest. *Fluminicola, Valvata,* and *Carinifex* racemize at intermediate rates, of which *Fluminicola* is the fastest. *Sphaerium* appears to racemize at a high rate, perhaps as high as *Amnicola,* although there is no direct basis of comparison.

**SOURCES OF VARIATION**

This section discusses possible sources of variation in the D/L data. I used the C.V. to quantify the scatter about the mean D/L for each sample. C.V. is typically below 10% for five well-preserved shells of a single population, although taxa with high natural variability may have coefficients of variation closer to 20% (Miller and Brigham-Grette, 1989). The average C.V. for my fossil data set is 12%, which is somewhat higher than expected. The frequency distribution of coefficients of variation from the fossil samples is skewed: 15% have coefficients of variation ≥20% (Fig. 12). This indicates that a few samples exhibit large variation between individual shells of the same genus collected from the same bed. When the 15% of the samples with coefficients of variation ≥20% are excluded from the calculation, the average C.V. is 9%, closer to the mode, which is 6%, and in agreement with Miller and Brigham-Grette's (1989) estimate.

To evaluate the intershell variation in D/L in laboratory-heated shells, I heated five pairs of *Lymnaea* and six pairs of *Valvata* at 142 °C for various lengths of time (Table 7). Because the temperature of the oven fluctuated over a few degrees, which may have significantly affected D/L, only samples heated in the oven at the same time were compared. In some cases, shells of the same genus prepared and heated at the same time yielded different D/L ratios. Four out of 11 pairs of shells yielded a C.V. <10%, two of the pairs had a C.V. higher than 20%, and the average C.V. was 13%.
Analytical Variation

**Stability of the Amino Acid Analyzer.** To monitor the amount of drift in D/L measured by the amino acid analyzer, the Utah State University Amino Acid Laboratory runs interlab calibration standards (ILC; Wehmiller, 1984) several times each year (Table 8). The data show little or no systematic variation through time. Given the reproducibility of analytical results (coefficients of variation <5%) and the lack of machine drift, I conclude that other factors must be responsible for the higher level of intershell variability obtained in this study.

**Intrashell Variation.** In a recent study, Sejrup and Haugen (1994) demonstrated that the fossil marine bivalve *Arctica* shows decreasing D/L ratios from the outer to the inner part of single-shell cross sections, suggesting that factors other than time and temperature affect racemization. They suggested that bacteria may consume L...
TABLE 7. D/L RATIOS IN DUPLICATE SHELLS OF THE SAME GENUS HEATED SIMULTANEOUSLY AT 142 °C

<table>
<thead>
<tr>
<th>UAL#</th>
<th>Genus</th>
<th>D/L</th>
<th>σ</th>
<th>C.V. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1458B</td>
<td>Lymnaea</td>
<td>0.13</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1459B</td>
<td>Lymnaea</td>
<td>0.13</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.13</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>1458C</td>
<td>Lymnaea</td>
<td>0.22</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1459C</td>
<td>Lymnaea</td>
<td>0.26</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.24</td>
<td>0.03</td>
<td>13</td>
</tr>
<tr>
<td>1458D</td>
<td>Lymnaea</td>
<td>0.35</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1459D</td>
<td>Lymnaea</td>
<td>0.37</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.36</td>
<td>0.01</td>
<td>3</td>
</tr>
<tr>
<td>1458E</td>
<td>Lymnaea</td>
<td>0.52*</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>1459E</td>
<td>Lymnaea</td>
<td>0.71</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.62</td>
<td>0.13</td>
<td>21</td>
</tr>
<tr>
<td>1499B</td>
<td>Lymnaea</td>
<td>0.42*</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1499C</td>
<td>Lymnaea</td>
<td>0.72</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.57</td>
<td>0.21</td>
<td>37</td>
</tr>
<tr>
<td>1501A</td>
<td>Valvata</td>
<td>0.05</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1502A</td>
<td>Valvata</td>
<td>0.07</td>
<td>0.01</td>
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<tr>
<td>Average</td>
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<td>0.01</td>
<td>17</td>
</tr>
<tr>
<td>1501B</td>
<td>Valvata</td>
<td>0.16</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1502B</td>
<td>Valvata</td>
<td>0.13</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.15</td>
<td>0.02</td>
<td>13</td>
</tr>
<tr>
<td>1501C</td>
<td>Valvata</td>
<td>0.30</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1502C</td>
<td>Valvata</td>
<td>0.26</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.28</td>
<td>0.03</td>
<td>11</td>
</tr>
<tr>
<td>1501D</td>
<td>Valvata</td>
<td>0.50</td>
<td>0.01</td>
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<td>1502D</td>
<td>Valvata</td>
<td>0.38</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.44</td>
<td>0.08</td>
<td>18</td>
</tr>
<tr>
<td>1501E</td>
<td>Valvata</td>
<td>0.83</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1502E</td>
<td>Valvata</td>
<td>0.73</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.78</td>
<td>0.07</td>
<td>9</td>
</tr>
<tr>
<td>1501F</td>
<td>Valvata</td>
<td>0.95</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1502F</td>
<td>Valvata</td>
<td>0.95</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.95</td>
<td>0.00</td>
<td>0</td>
</tr>
</tbody>
</table>

* Samples strayed from expected trend and showed evidence of contamination; therefore, they were excluded from any calculations other than those performed in this table.
TABLE 8. D/L RATIOS MEASURED IN INTERLABORATORY COMPARATIVE STANDARDS (ILC, WEHMILLER, 1984) AT THE UTAH STATE UNIVERSITY LABORATORY

<table>
<thead>
<tr>
<th>Date</th>
<th>UAL #</th>
<th>ILC-A Avg D/L</th>
<th>ILC-B Avg D/L</th>
<th>ILC-C Avg D/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>σ</td>
<td>σ</td>
<td>σ</td>
</tr>
<tr>
<td>4/93</td>
<td>1000-1002</td>
<td>0.152</td>
<td>0.527</td>
<td>1.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.001</td>
<td>0.014</td>
<td>0.006</td>
</tr>
<tr>
<td>1/94</td>
<td>1113-1115</td>
<td>0.159</td>
<td>0.551</td>
<td>1.154</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.002</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>5/94</td>
<td>1113-1115</td>
<td>0.157</td>
<td>0.549</td>
<td>1.115</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.007</td>
<td>0.002</td>
<td>0.033</td>
</tr>
<tr>
<td>9/94</td>
<td>1375-1377</td>
<td>0.155</td>
<td>0.531</td>
<td>1.092</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.003</td>
<td>0.001</td>
<td>0.004</td>
</tr>
<tr>
<td>11/94</td>
<td>1375-1377</td>
<td>0.156</td>
<td>0.532</td>
<td>1.145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.004</td>
<td>0.003</td>
<td>0.009</td>
</tr>
<tr>
<td>2/95</td>
<td>1375-1377</td>
<td>0.151</td>
<td>0.525</td>
<td>1.122</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.002</td>
<td>0.007</td>
<td>0.015</td>
</tr>
<tr>
<td>4/95</td>
<td>1375-1377</td>
<td>0.154</td>
<td>0.523</td>
<td>1.121</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.004</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.154</td>
<td>0.523</td>
<td>1.121</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.003</td>
<td>0.011</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Amino acids during the early stages of diagenesis, attacking along the growth lines of the shell. Brigham (1983) also found that the growth edge of the marine bivalve *Hiattella arctica* is depleted in amino acids compared to the hinge or central part of the shell. She attributed this phenomenon to leaching from the thinner edge, or to a protein-rich inner layer at the hinge and central part of the shell.

During the course of this study, it became apparent that different parts of a single mollusc shell may have yielded different D/L ratios. A test was performed whereby two *Valvata* collected from a single bed (Fig. 8, Site 3) and two *Carinifex* collected from a single bed (Fig. 8, Site 4) were each divided into three sections: outer whorl, mid-section, and spire. The D/L ratios were obtained following standard laboratory procedures, each shell fragment treated identically. The results of this test show no systematic trend, except perhaps that the outer whorl is slightly more racemized than the other parts (Table 9). The data also show that, within one shell, the D/L ratios vary from
2 to 12%. The paucity of data do not allow any firm conclusions to be drawn, but these preliminary data are consistent with the variation expected for a single population. Five out of eight analyses overlap with their neighbors within ±1σ analytical variation.

### TABLE 9. INTRASHELL VARIATION IN D/L WITHIN FOUR SHELLS

<table>
<thead>
<tr>
<th>UAL#</th>
<th>Genus</th>
<th>Shell part</th>
<th>D/L</th>
<th>σ*</th>
<th>C.V. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1486A</td>
<td>Valvata</td>
<td>Outer Whorl</td>
<td>0.52</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1486B</td>
<td>Valvata</td>
<td>Midsection</td>
<td>0.50</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1486C</td>
<td>Valvata</td>
<td>Spire</td>
<td>0.46</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>0.49</td>
<td>0.03</td>
<td>6</td>
</tr>
<tr>
<td>1486D</td>
<td>Valvata</td>
<td>Outer Whorl</td>
<td>0.54</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1486E</td>
<td>Valvata</td>
<td>Midsection</td>
<td>0.53</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1486F</td>
<td>Valvata</td>
<td>Spire</td>
<td>0.53</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>0.53</td>
<td>0.01</td>
<td>2</td>
</tr>
<tr>
<td>1487A</td>
<td>Carinifex</td>
<td>Outer Whorl</td>
<td>0.26</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1487B</td>
<td>Carinifex</td>
<td>Midsection</td>
<td>0.19</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1487C</td>
<td>Carinifex</td>
<td>Spire</td>
<td>0.22</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>0.23</td>
<td>0.03</td>
<td>13</td>
</tr>
<tr>
<td>1487D</td>
<td>Carinifex</td>
<td>Outer Whorl</td>
<td>0.18</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1487E</td>
<td>Carinifex</td>
<td>Midsection</td>
<td>0.17</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1487F</td>
<td>Carinifex</td>
<td>Spire</td>
<td>0.15</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>0.17</td>
<td>0.02</td>
<td>12</td>
</tr>
</tbody>
</table>

* The standard deviation is the analytical error for a single sample solution, the internal reproducibility.
The intrashell data can be used to assess which genus shows greater consistency in D/L across a single valve (Table 9). The average intrashell C.V. for the two *Carinifex* is 12%, whereas the average C.V. for the two *Valvata* is 4%, within analytical resolution, suggesting that the intrashell variation is higher for *Carinifex* than for *Valvata*. In some cases, intrashell variation may be partly responsible for the scatter in the data, but is not always the primary contributor. Most shells analyzed in this study were whole, so intrashell variation is irrelevant.

The results from the duplicate shells used for the intrashell study (Table 9) can also be used to address intershell variation. All parts of one *Valvata* yielded lower D/L ratios than in comparable parts of its counterpart, except for the outer whorl where the D/L ratios overlap at ±1σ. The same is true for *Carinifex*, the exception being overlap at ±1σ for the midsection. This suggests that, based on these limited data, the variation between individual shells of the same genus collected from the same bed is more important than the variation within a shell.

**Variation in Sample Preparation.** Because smaller shells (by mass) were acid-cleaned less than larger ones, and some shells were not leached at all, I was concerned that the D/L ratios were influenced by the extent of acid leaching. To test this effect, I sampled six shells collected from a single bed that yielded similar D/L ratios (C.V. = 6%) and prepared them by varying the volume of 2 N HCl used for cleaning. The results show no systematic trend in D/L versus extent of acid leach (Table 10). The C.V. for the six shells is 11%, which is consistent with the variation expected for a single population. The two shells that were leached 30% each account for a large portion of the variability, yet they were prepared identically. Although the data are insufficient to draw firm conclusions, the extent of acid leach apparently does not significantly contribute to intra-generic variation of D/L ratios in fossils of a single bed.
### Table 10. D/L Ratios Measured in Shells of a Single Population Subjected to Varying Amounts of Acid Leach

<table>
<thead>
<tr>
<th>UAL #</th>
<th>% Acid leach (by shell weight)</th>
<th>D/L</th>
<th>σ*</th>
<th>C.V. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1485A</td>
<td>0</td>
<td>0.22</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1485D</td>
<td>0</td>
<td>0.20</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1485E</td>
<td>13</td>
<td>0.17</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1485C</td>
<td>23</td>
<td>0.18</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1485B</td>
<td>30</td>
<td>0.21</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1485F</td>
<td>30</td>
<td>0.18</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.19</td>
<td>0.02</td>
<td>11</td>
</tr>
</tbody>
</table>

* The standard deviation is the analytical error for a single sample solution, the internal reproducibility.

### Geologic Variation

**Reworking.** In many geological environments, shells from older deposits are reworked into younger deposits prior to final burial. A quantitative assessment of the extent of reworking is difficult. Although I cannot rule out the possibility that reworking is responsible for the high C.V. seen in some samples, I suggest that the samples were collected from single-age populations because most shells analyzed were unabraded and whole. *Sphaerium* was frequently collected as paired valves. Often the genera collected were not found anywhere in the vicinity of the collection site, indicating that there was no immediate source of older shells. Reworking can also be eliminated as the cause for variation in D/L between modern shells used in the lab-heating experiments.

**Diagenesis.** In fossils, amino acids are part of a complex biogeochemical system. Proteins degrade into smaller polypeptides, which, in turn, degrade into free amino acids. These amino acids can decompose into non-amino-acid molecules, can be consumed by microbes, or can be leached; all of these processes affect the D/L ratio.
measured in the total acid hydrolysate population. These chemical and physical diagenetic processes that affect mollusc shells are poorly understood.

The carbonate matrix of molluscs is susceptible to removal of amino acids by groundwater leaching (Earnst, 1987). Assuming that free amino acids, the most highly racemized fraction, are preferentially removed, then the D/L ratio is lowered in a leached shell compared to a non-leached fossil of the same age. The extent of leaching is dependent upon the amount of groundwater percolating through the sediments, the shell structure, and the preservation of the shell. Whether leaching was responsible for the high variation in some of my samples is equivocal.

**Contamination.** In addition to leaching, penetration of microbial-rich water into a fossil shell may result in the introduction of contaminants (Mitterer, 1993). Amino acids in the surrounding sediments or other organisms in contact with the shell might also contaminate the fossil (Mitterer, 1993). Although caution is taken (gloves are worn and only sterile equipment is used), some contamination may enter during shell preparation in the laboratory. The modern molluscs were carefully examined before analysis, but some soft-body parts may have been included in the preparation, resulting in the incorporation of non-shell-derived amino acids into the analyses.

Contaminated sample preparations are routinely identified in geologic investigations because they exhibit high concentrations of the unstable amino acid serine relative to the stable amino acid threonine, and because they typically have D/L ratios lower than uncontaminated preparations of the same age and genus (Wehmiller, 1993). I used this criterion to identify contaminated preparations and noted that, in some cases, molluscs with D/L ratios that deviated from expected trends did not show a high serine/threonine ratio. Conversely, some shells with D/L ratios that did conform to expected trends also showed a high serine/threonine ratio. For this reason, all data were
included in this study except three shells from the lab-heating experiments. Contamination of two Lymnaea and one Amnicola was evident, the determination of which was based upon D/L ratios that deviated from trends of other lab-heated shells of the same genus, and supported by the fact that these shells also had disproportionate serine and threonine peaks.

**Taxonomic Variation**

**Generic Consistency.** The reliability of different molluscan genera for amino acid geochronology is known to vary (Miller and Brigham-Grette, 1989). In an effort to determine which genera produced the most consistent results and whether a particular genus was responsible for the highest-variation samples from Thatcher Basin, I evaluated the coefficients of variation for the four most common genera (Fig. 12). Carinifex, Sphaerium, Valvata, and Fluminicola all include at least one sample with a C.V. ≥20%. The average coefficients of variation for Sphaerium, Fluminicola, Valvata, and Carinifex are 8, 10, 12, and 16%, respectively. Based on this analysis, the four genera are approximately equally reliable, except perhaps Carinifex, with the highest C.V. This is consistent with the findings of the intrashell variation experiment that showed greater variation for Carinifex than for Valvata.

**Species-Level Variations.** Lajoie and others (1980) concluded that the rate of racemization is uniform for all species within a genus. Recent evidence from the Utah State University Amino Acid Laboratory, however, has documented variation in D/L at the species level for Lymnaea. Results of lab-heating experiments performed on Lymnaea bonnevillensis and Lymnaea elodes suggest that their rates of racemization differ. No species-level distinction was made in this study. Samples that included more than one species may account for some variation. This is of concern particularly for
Carinifex and Valvata because often more than one species was collected and analyzed per bed; the D/L ratios of multiple-species comprised a single sample.

**SUMMARY AND CONCLUSION**

Based upon the lab-heating experiments, *Amnicola* racemizes faster than *Lymnaea*. Abundant data from the fossil record support this finding. This lends confidence to the equation (eq. 2) derived from the combined fossil and lab-heated data to convert D/L in *Amnicola* to D/L in *Lymnaea*, and vice versa. The 95% confidence intervals for the rate constants derived from the 142 °C lab-heating experiments indicate that there is a significant difference between the rate of racemization of *Lymnaea* and *Amnicola*, but that there are no discernible differences between the rates of racemization in *Lymnaea* and *Sphaerium*, *Valvata* and *Lymnaea*, and *Amnicola* and *Valvata*. An alternate analysis of the lab-heated data, based on a direct comparison of two genera, however, reveals that *Amnicola* racemizes 21% faster than *Valvata*, *Valvata* racemizes 17% faster than *Lymnaea*, and *Sphaerium* racemizes 26% faster than *Lymnaea*. Because the limited fossil data for these pairs show no apparent trend, whether lab-heating experiments for these shell pairs mimic natural diagenesis is unclear. Limited fossil data from multiple-genera beds in Thatcher Basin indicate the rates of racemization between *Carinifex* and *Valvata* are indistinguishable and *Fluminicola* may racemize faster than *Carinifex*.

The variability (C.V.) in D/L ratios in mono-generic samples collected from the same bed averages 12%. The frequency distribution of coefficients of variation is skewed: 15% of the samples have coefficients of variation ≥ 20% and the remaining 85% have an average C.V. of 9%. The variability in D/L for most samples analyzed in this study is at the expected level (Miller and Brigham-Grette, 1989). At least one sample of
the four most common fossil genera, Carinifex, Sphaerium, Valvata, and Fluminicola, had a C.V. \( \geq 20\% \). Their mean coefficients of variation suggest that the four genera are about equally reliable, except Carinifex, which may be less consistent. When two shells of the same genus were heated simultaneously at 142 °C, 4 out of 11 yielded coefficients of variation <10%. The variation in D/L between three parts of two Valvata and two Carinifex shells is generally consistent with the variation expected for a single population. Greater intrashell variation was documented for Carinifex (13%) than for Valvata (4%).

No single cause can be identified that accounts for all of the variation in the data. The higher-than-expected variation (C.V. >20%) measured in ~15% of the samples cannot be attributed to analytical variation (C.V. <5%). Intrashell variation accounts for <13% of the variability in the case of Carinifex and 4% for Valvata, but is not a factor for most of the samples analyzed, which comprised whole shells. Apparently, the extent of acid cleaning is also not a factor. Although the variation caused by geologic factors is more difficult to quantify, thin, fragile shells, like those analyzed in this study, tend to exhibit higher variation than thick, robust shells as a result of leaching and subtle aspects of diagenetic reactions that are, as of yet, incompletely understood. Samples may also be composed of reworked shells of different ages. Taxonomic variation may contribute some variation, primarily for samples composed of more than one species. At the generic level, the genera most commonly found in Thatcher Basin appear to be equally reliable for aminosratigraphy. All factors, analytical, taxonomic, and geologic, work together to create the variation in D/L ratios. More research is needed to address the physical and chemical processes that control racemization during fossil diagenesis.
CHAPTER 3
LAKE-LEVEL HISTORY IN THATCHE R BASIN

INTRODUCTION

Reconstructing the history of lake-level fluctuations requires two equally important data sets: (1) the elevation of the shoreline (depth of the lake) and (2) the age at which the lake occupied that position. To assess the position of lake level, I used a topographic map to obtain elevations for particular beds. Stratigraphic columns from four localities across southern Thatcher Basin were constructed: sediment characteristics provided a means to interpret the depositional environment. D/L ratios in fossil molluscs, in conjunction with buried soils and tephra, were used to correlate between localities. Relative ages were assessed by comparing D/L ratios, and tephra, which are useful as time stratigraphic markers, provided absolute ages. D/L ratios also provided absolute ages when used in conjunction with an amino acid calibration curve. To calibrate the rate of amino acid racemization in shells from Thatcher Basin, I used independently dated shells (radiocarbon and tephrochronology) and their associated D/L ratios. Other nondated lake deposits were then assigned ages by interpolating along the calibration curve, providing the basis for the late-Pleistocene Lake Thatcher chronology. The age of shells collected at the top of the Main Canyon Formation is especially important because it provides a maximum age for the breaching of the former drainage divide at Oneida Narrows and entry of the through-flowing Bear River into the Bonneville Basin.

METHODS

Stratigraphic columns were measured and described, and shells were collected at four sites in southern Thatcher Basin (Table 11; Fig. 8). The sites were chosen because
TABLE 11. LOCATION OF SITES SAMPLED IN THATCHER BASIN, IDAHO

<table>
<thead>
<tr>
<th>Site #</th>
<th>Quad</th>
<th>Location</th>
<th>Township/range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Thatcher, ID</td>
<td>Main Canyon Dugway</td>
<td>SW1/4 sec. 8, T. 12 S. R. 41 E.</td>
</tr>
<tr>
<td>1b, c, d</td>
<td>Thatcher, ID</td>
<td>Main Canyon Dugway</td>
<td>SE1/4 sec. 7, T. 12 S. R. 41 E.</td>
</tr>
<tr>
<td>2</td>
<td>Thatcher, ID</td>
<td>Route 34</td>
<td>NW1/4 sec. 7, T. 12 S. R. 41 E.</td>
</tr>
<tr>
<td>3a, b, c</td>
<td>Thatcher Hill, ID</td>
<td>Johnny's Hole</td>
<td>SW1/4 sec. 15, T. 11 S. R. 40 E.</td>
</tr>
<tr>
<td>4</td>
<td>Thatcher Hill, ID</td>
<td>Carter Lane</td>
<td>SW1/4 sec. 8, T. 11 S., R. 40 E.</td>
</tr>
</tbody>
</table>

they: (1) contained exposures of the Main Canyon and Bonneville alloformations spanning a long (~100 ka) time period; (2) contained shells; and (3) were readily accessible. At a fifth site (Site 5, Fig. 8), an overlying basalt flow may have enhanced racemization in fossil mollusc shells near the flow. Therefore, this site was not used for chronostratigraphic purposes (although it does contain a tephra not found elsewhere in the basin).

At each site, sediments were described according to standard practice (color, grain size, sorting, and grain shape). Bed thickness was measured to the nearest centimeter and the nature of the contact between beds was noted. Primary sedimentary features and structures were noted, although some beds were so finely laminated and indurated that they may have been incorrectly identified as massive. In some instances, lamination went undetected until blocks of sediment samples were submerged in water in the laboratory prior to sieving for molluscs; upon saturation, the lamination became noticeable. Fossils were collected, and their distribution, position, and condition were recorded. Faults were documented and the amount of offset was measured. Evidence of
pre-Holocene soil development was recorded; in most cases individual horizons were measured and briefly described.

Sediment that appeared to contain glass shards was collected as potential tephra. In several cases ash beds were distinctive, but in most cases the presence of disseminated tephra in lake deposits was ambiguous. In the laboratory, these samples were dissolved in 10% HCl to remove carbonate. The insoluble material was sent to William Nash (University of Utah) to confirm the presence of tephra and analyze its elemental and oxide abundances using an electron microprobe. He compared the results to his database of Great Basin ashes for identification. Seven out of 18 samples yielded sufficient glass for analyses. The results of one fine-grained tephra, whose source was likely the Cascade Mountains, were compared to the data base of Andrei Sarna-Wojcicki (U.S. Geological Survey).

STRATIGRAPHY
Site 1

Description. Site 1 (Figs. 8 and 13), the Main Canyon Dugway, is the type locality of Bright's Main Canyon Formation (Bright, 1963). This site is located on the east side of the basin and exposes a delta formed into Lake Thatcher at the mouth of Kuntz Creek. It is composed of several small (<5 m) roadcut exposures. In total, the four sections sampled (a, b, c, and d) are separated laterally by several hundred meters and vertically by ~60 m. Only 14 m of section were exposed for sampling; 77% of Site 1 is covered. The uppermost bed at section 1a was deposited at the highest Lake Thatcher terrace at 1,660 m asl. Below this, successive sections (1b, 1c, and 1d) descend along the dugway, with the lowest bed at 1,598 m asl.
Figure 13. Stratigraphic columns of the four sites sampled (Fig. 8) in Thatcher Basin, Idaho. Elevations are in meters above sea level.
Site 1

1608 - COVERED

1607 -

1606 -

1605 -

1604 -

1601 -

1600 -

1599 -

1598 - COVERED

ox, ws, m, t/t

ox, org, ws, m, t

ox, org, ws, m, t

ox stringers, org, t

org, m, ws, t

m, t

ox stringers, m, ws, t

ox, org, ws, m, w/t

m, t

org, xl, ws, m, t

ox, org, xl, ws, m, t

ox stringers, org, xl, ws, m, b/t

ox, org, ws, lam, t/g

proto Mount St. Helens tephra

org, ws, lam, g

UAL 1404  D/L = 0.24 (Val)

UAL 1351  D/L = 0.24 (Car)

UAL 1396, 1584  D/L = 0.18 (Val)

UAL 1432, 1583  D/L = 0.21 (Val)

UAL 1585  D/L = 0.27 (Car)

UAL 1586  D/L = 0.28 (Sph)

UAL 1403, 1587  D/L = 0.21 (Val)

UAL 1588  D/L = 0.18 (Car)

UAL 1589  D/L = 0.26 (Flu)

UAL 1449  D/L = 0.21 (Val)

Figure 13. (Continued).
Site 2

1524 - COVERED

1523 - Bt
K
Bt
K

1522 - COVERED

1521 - COVERED

1520 - COVERED

m, r/b
UAL 1446 D/L = 0.21 (Val)
m, w
UAL 1349 D/L = 0.18 (Val)
tephra of unknown source

Figure 13. (Continued).
Figure 13. (Continued).
Figure 13. (Continued).
Site 3

![Diagram of Site 3 with stratigraphic layers and associated artifacts]

Figure 13. (Continued).
Figure 13. (Continued).
Figure 13. (Continued).
### EXPLANATION:

<table>
<thead>
<tr>
<th>Bonneville Formation</th>
<th>ox</th>
<th>oxidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Canyon Formation</td>
<td>org</td>
<td>organic</td>
</tr>
<tr>
<td>calcite or gypsum crystals</td>
<td>ws</td>
<td>well sorted</td>
</tr>
<tr>
<td>poorly sorted</td>
<td>ps</td>
<td>poorly sorted</td>
</tr>
<tr>
<td>massive</td>
<td>m</td>
<td>massive</td>
</tr>
<tr>
<td>laminated</td>
<td>lam</td>
<td>laminated</td>
</tr>
<tr>
<td>graded</td>
<td>grd</td>
<td>graded</td>
</tr>
<tr>
<td>Sphaerium (Sph)</td>
<td>b</td>
<td>brown</td>
</tr>
<tr>
<td>gray</td>
<td>g</td>
<td>gray</td>
</tr>
<tr>
<td>green</td>
<td>gr</td>
<td>green</td>
</tr>
<tr>
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<td>o</td>
<td>orange</td>
</tr>
<tr>
<td>pink</td>
<td>p</td>
<td>pink</td>
</tr>
<tr>
<td>red</td>
<td>r</td>
<td>red</td>
</tr>
<tr>
<td>tan</td>
<td>t</td>
<td>tan</td>
</tr>
<tr>
<td>white</td>
<td>w</td>
<td>white</td>
</tr>
<tr>
<td>Tryonia (Try)</td>
<td>A</td>
<td>organic A horizon</td>
</tr>
<tr>
<td>calcified horizon</td>
<td>K</td>
<td>calcified horizon</td>
</tr>
<tr>
<td>Carinifex (Car)</td>
<td>Bk</td>
<td>calcic B horizon</td>
</tr>
<tr>
<td>textural B horizon</td>
<td>Bt</td>
<td>textural B horizon</td>
</tr>
<tr>
<td>weathered B horizon</td>
<td>Bw</td>
<td>weathered B horizon</td>
</tr>
<tr>
<td>oxidized C horizon</td>
<td>Cox</td>
<td>oxidized C horizon</td>
</tr>
<tr>
<td>soil</td>
<td>soil horizon boundary</td>
<td>(if different than bedding plane)</td>
</tr>
<tr>
<td>soil horizon boundary</td>
<td>soil horizon boundary</td>
<td>(if different than bedding plane)</td>
</tr>
<tr>
<td>unconfornity surface</td>
<td>unconfornity surface</td>
<td>(if different than bedding plane)</td>
</tr>
<tr>
<td>grain size key</td>
<td>break in section</td>
<td>break in section</td>
</tr>
<tr>
<td>clay</td>
<td>cl</td>
<td>clay</td>
</tr>
<tr>
<td>silt</td>
<td>s</td>
<td>silt</td>
</tr>
<tr>
<td>fine sand</td>
<td>f</td>
<td>fine sand</td>
</tr>
<tr>
<td>medium sand</td>
<td>m</td>
<td>medium sand</td>
</tr>
<tr>
<td>coarse sand</td>
<td>c</td>
<td>coarse sand</td>
</tr>
<tr>
<td>gravel</td>
<td>g</td>
<td>gravel</td>
</tr>
</tbody>
</table>

**Figure 13. (Continued)**
The sediments of the uppermost section (1a) are carbonate-rich, massive silt to pebbly gravel and contain no sedimentary structures. The entire exposure is ~2 m thick and contains five laterally continuous beds that are separated by sharp contacts. The lowest bed (~30 cm thick) is composed of medium sand and is overlain by ~25 cm of gravel. The overlying ~1.5 m are composed of silt with the exception of a pebbly shell-rich layer, ~5-cm-thick, 1 m below the top of the exposure.

The shells of four molluscan genera are found throughout the upper 1 m of section 1a, but are most concentrated in the ~5-cm-thick, gravelly bed that underlies it. Fossil shells of Carinifex, Fluminicola, and Sphaerium are plentiful, but only two Lymnaea shells were found after a thorough search that included sieving ~100 liters of sediment. A majority of shells in this fossiliferous bed are whole; many are slightly oxidized and speckled.

The ~5-cm-thick fossiliferous layer lies below the modern soil, 1 m thick, and above a >1-m-thick paleosol. Because section 1a exposes the uppermost sediment of the Main Canyon Formation, the presence of a paleosol below the modern soil is extremely significant because it indicates a lake-level recession prior to the final rise of Lake Thatcher. The fossiliferous layer within the upper 1 m of section 1a was distinguished from the underlying paleosol by color and texture (Fig. 14). The soil is oxidized, redder than the sediments above and below it, which are unoxidized and tan. The soil structure, which includes a 1-m-thick silty Bw and a 20-cm-thick sandy Cox horizon, is not well defined, probably owing to the sandy parent material. The paleosol is somewhat indurated because of an accumulation of calcium carbonate in the B horizon (Harden, 1982).
Figure 14. Modern soil underlain by a paleosol at the top of the Main Canyon Dugway (section 1a). Light-colored bed in the middle of the photo is a shell-rich layer in which *Sphaerium* are visible.
The sediments of sections 1b, 1c, and 1d (elevation 1,598-1,617 m asl) are carbonate rich and predominantly tan. The sediments of section 1b generally coarsen upward, with a progression from laminated silt to laminated medium sand. All contacts between beds are gradational. The only fossil shells found at section 1b were *Sphaerium*, collected as paired valves. The sediments of section 1c and 1d range from clay to fine sand and are richly fossiliferous, containing three genera of molluscs. Unlike section 1b, contacts between beds are sharp at section 1c and 1d. A ~20-cm-thick, organic-rich bed was uncovered in section 1c at 1,606 m asl. While unsuccessfully searching for the Hebgen Narrows tephra, which was reported at the Main Canyon Dugway (Izett, 1981), a 6-cm-thick, fine-grained, carbonate-free, white ash (AH95-3p; Table 12) was collected at 1,598 m asl in section 1d between finely laminated sediments. It was correlated with the proto Mount St. Helens tephra as discussed in more detail later in the Geochronology section. The tephra is coarser at the base and is speckled with mafic minerals.

### TABLE 12. TEPHRA FOUND IN THATCHER BASIN

<table>
<thead>
<tr>
<th>Tephra</th>
<th>Field ID #</th>
<th>Site # (Fig. 6)</th>
<th>Age (ka)</th>
<th>D/L*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>proto Mount St. Helens</td>
<td>AH95-3p</td>
<td>1</td>
<td>90±10</td>
<td>0.18 ± 0.01</td>
<td>this study</td>
</tr>
<tr>
<td>unidentified</td>
<td>AH94-18b</td>
<td>2</td>
<td></td>
<td>&gt;0.20</td>
<td></td>
</tr>
<tr>
<td>Lava Creek B</td>
<td>AH94-19a</td>
<td>3</td>
<td>620</td>
<td>0.4 ± 0.1</td>
<td>Sarna-Wojcicki and others, 1991</td>
</tr>
<tr>
<td>Huckleberry Ridge</td>
<td>AH94-x</td>
<td>3</td>
<td>2000</td>
<td>&gt;0.07</td>
<td>Sarna-Wojcicki and others, 1991</td>
</tr>
<tr>
<td>proto Mount St. Helens</td>
<td>AH95-8k</td>
<td>4</td>
<td>90±10</td>
<td>0.20 ± 0.04</td>
<td>this paper</td>
</tr>
<tr>
<td>Rye Patch Dam</td>
<td>AH94-1b</td>
<td>5</td>
<td>630</td>
<td></td>
<td>Sarna-Wojcicki and others, 1991</td>
</tr>
</tbody>
</table>

* D/L ratios for Sites 1, 2, and 4 were measured in *Lymnaea*, whereas D/L ratios at Site 3 were measured in *Valvata.*
**Interpretation.** Most, if not all of the sediments exposed at Site 1, like all other sites measured in this study, are believed to have been deposited in a lake. This diagnosis is based on the following observations: (1) sediments are well sorted; (2) beds are laterally continuous with conformable contacts; (3) many beds are finely laminated; (4) tephra at section 1d is graded; and (5) molluscs are lacustrine, although many inhabit other environments as well.

Compared to sections 1a, b, and c, section 1d records the earliest history of Lake Thatcher, as the proto Mount St. Helens tephra fell into a lake that was >1,600 m asl. Nearly 3 m of lake sediment was deposited upon the ash. Section 1c is probably younger than 1d owing to its higher elevation. The lowest two beds of section 1a, younger than those of section 1b based on elevation, are poorly sorted, massive, and are composed of coarse-grained sand and gravel that was likely deposited at the shore of Lake Thatcher (1,658 m asl). Directly above these beds are ~70 cm of oxidized silt. A paleosol is formed into the three lowest beds of section 1a, recording a lake-level recession during the initial late-Pleistocene highstand of Lake Thatcher. The paleosol is overlain by ~1 m of sediment, dividing two lake cycles at Site 1, both reaching ~1,660 m asl. A thin shell-rich bed, a lag deposit, at 1,659 m asl formed from shoreline reworking during the final transgression of Lake Thatcher. This lag deposit is overlain by 1 m of silt to fine sand, but because it is massive, it is not certain whether it is lacustrine or perhaps loess or a floodplain deposit. It is tan and carbonate rich, and contains fossil shells throughout, of which all genera were found elsewhere throughout the Main Canyon Formation.

**Site 2**

**Description.** Site 2 (Figs. 8 and 13) is a small (4 m high) exposure along the east side of Idaho Route 34. The exposure is formed into a recent landslide that contains
translocated blocks. Slumped sediments covering the top half of the roadcut are red/brown, whereas those at the base are light colored. The contact between the red/brown and light-colored sediments is covered. A (~90 cm thick) composite soil directly below the uppermost bed (at 1,523 m asl) in the red sediment contains what appears to be two K horizons (~10 cm thick) and two B₄ horizons (~75 cm thick). The K horizons are white, chalky bands whose upper and lower contacts are wavy. The 0.5-m-thick exposure of white silt at 1,521 m asl is typical of Lake Thatcher sediment: It is carbonate-rich and the Valvata population is dense. The fossil shells collected from the light-colored sediment were plentiful and well preserved, unlike those at 1,522 m asl, in the red sediment, which were sparse. While searching for the Lava Creek B tephra, which was previously discovered here (Izett, 1981), another coarse-grained, gray tephra (AH94-18b) at the base of the exposure was partially uncovered, exposing >20 cm of ash (Table 12).

**Interpretation.** Bright (1963) claimed that the red sediment in Thatcher Basin was deposited in Lake Bonneville. Because shells with D/L ratios similar to those in sediment of the most recent highstand of Lake Bonneville are seldom found in Thatcher Basin, it is uncertain, based on amino acid geochronology, whether the red sediment at Site 2 was deposited in Lake Bonneville and contains reworked Lake Thatcher shells, or whether it was deposited in Lake Thatcher prior to the Bonneville highstand. The top of Site 2 is 1,524 m asl, just below the elevation of the Lake Bonneville shoreline. The paleosol in the red sediment suggests that deposition was not continuous. Either Lake Bonneville receded twice and subaerial exposure allowed for pedogenesis, or Lake Thatcher receded below 1,524 m asl before Lake Bonneville entered the basin. It is also possible that the red sediments are Bear River fluvial deposits. Based on the red color and low carbonate content of the sediment, and on the fact that the bed is laterally
continuous, I believe that the red sediment was deposited in Lake Bonneville on top of Lake Thatcher sediment in a shallow-water environment. Also, in support of this conclusion are D/L ratios at Site 2 do not follow in stratigraphic sequence. The D/L ratios of shells collected from the white sediment are typical of D/L ratios at the top of Site 1, but are overlain (in red sediment) by older shells (higher D/L ratios). This implies that the shells in the red sediment may be reworked, which is supported by their erratic distribution: The shells in the red sediment are sparse, unlike most beds in Thatcher Basin in which the shell concentration is dense.

Site 3

**Description.** Site 3 (Figs. 8 and 13), near the Thatcher Church (known locally as Johnny's Hole), is the elevationally lowest site sampled in this study, near the current elevation of the Bear River (1,500 m asl). Several exposures at Site 3 were formed by land sliding, probably enhanced by the construction of an irrigation ditch running the entire length of the ~1-km-long site. Four sections were sampled.

The beds at Site 3 are variable in color, with abrupt changes between adjacent beds (Fig. 15). The contacts between beds, particularly at section 3c, are sharp. Sediments are mostly light-colored silt and fine sand, interstratified with dark, organic-rich beds. The 13 organic-rich layers, ranging in thickness from 2 to ~40 cm, are composed of decayed plant matter. Six paleosols have been identified, ranging in thickness from ~20 to 250 cm.

At section 3c, fossil snails, especially *Valvata*, are abundant (Fig. 15). The fossils were well preserved, whole shells and often comprised pure shell layers, but were also found scattered throughout the sediment. Section 3c contains 8 of the 13 organic-rich beds and three of the six paleosols found at Site 3. Similar to the two paleosols at
Figure 15. Three paleosols at section 3c, Thatcher Basin, Idaho. Figure on left shows closeup of prismatic soil structure.
section 3d, at 1,541 m asl, the paleosols at section 3c are distinctly gray/green, exhibit prismatic structure, and include a chalky, white soil carbonate horizon (K) several tens of centimeters thick (Fig. 15). Also, the upper and lower boundaries of the K horizon are irregular, unlike the nearly planar contacts of lacustrine sediment. The five soils of this description are most obvious when moistened to accentuate their color and prismatic structure.

The lower 8 m of section 3b are light-colored clay and silt beds, separated by gradational contacts and overlain by ~1.5 m of brown/red, massive fine sand with angular clasts of mud. The brown/red sediment extends up to the Bonneville shoreline elevation. The red and white sediments are separated by an angular unconformity (Fig. 16). *Valvata* were collected at 1,549 m asl, in the uppermost bed of the light-colored sediment. The red sediment contains *Lymnaea* and *Sphaerium*, but only *Valvata* of significant quantity to be analyzed for amino acid geochronology. Many shells collected from the red sediment were broken, making identification difficult.

Izett (1981) previously identified Huckleberry Ridge tephra (Fig. 17) and Lava Creek B tephra at this outcrop (Fig. 18). These coarse-grained, light-gray tephra, (AH94-x and AH94-19a, respectively) were recollected for this study and their identities were confirmed by Nash (Table 12). At section 3a, the Huckleberry Ridge ash is at least 2.5 m thick and the Lava Creek B ash at section 3d is at least 2 m thick, although the lower contacts of both were not exposed. No fossil molluscs were found adjacent to either tephra and no structures were identified in the Huckleberry Ridge ash, but the Lava Creek B tephra contains small-scale cross beds (not visible in picture). The ashes can be distinguished from lake sediment because they are (1) carbonate-free, (2) unconsolidated, and (3) composed of glass shards visible with the naked eye. A 1-m-thick paleosol with blocky texture that is slightly oxidized is developed into the Lava Creek B ash (Fig. 18).
Figure 16. Red sediment resting unconformably upon light-colored sediment at the top of section 3b, Thatcher Basin, Idaho.
Figure 17. Huckleberry Ridge tephra at section 3a, Thatcher Basin, Idaho.
Figure 18. Paleosol developed into Lava Creek B tephra and overlying silt and sand beds at section 3d, Thatcher Basin, Idaho.
Interpretation. The six paleosols at Site 3 suggest that at least that many lake-level fluctuations are represented. Because these soils are located near the basin floor, they require that lake level was low or the basin was dry. Organic-rich beds contain grasses and other plants including cattail, sedge, pondweed, and bur-reed that grow in shallow-water, paludal environments (Bright, 1963). The presence of Valvata supports this interpretation because they are presently found in shallow, vegetated water of slow streams and lakes (P. Hovingh, personal communication, 1995). Minor water-level oscillations probably caused alternating deposition of dark, organic-rich sediment in shallow water and light-colored, inorganic silt and fine sand in deeper water (>1,541 m asl).

Similar to Site 2, whether the red sediment at section 3b was deposited in Lake Bonneville or Lake Thatcher, or by the Bear River itself is unclear. The uppermost ~1.5 m of red sediment at section 3b reaches 1,550 m asl, 5 m below the Lake Bonneville shoreline, suggesting that the red sediment may have been deposited in Lake Bonneville. Several attributes of section 3b, same as those presented for Site 2, favor this interpretation: (1) the red color of the sediment; (2) the low carbonate content of the sediment; (3) the poor preservation and the random distribution of fossil molluscs; and (4) D/L ratios that do not follow in stratigraphic sequence. However, unlike Site 2, the red sediment at section 3b cuts unconformably into the white sediment and contains angular clasts that may be rip-up clasts. These lines of evidence hint at deposition in a high-energy environment. Perhaps, the red sediment was deposited in Lake Bonneville and then slid to its present position. Alternatively, the red sediment may also be alluvium, emplaced as the Bear River cut into Lake Thatcher sediment.

To assess whether the tephra are interbedded with lake sediments is valuable because it indicates that the basin contained a lake at a given time. Because the base of
the Huckleberry Ridge tephra is not exposed, and the upper contact is buried, whether or not the ash was deposited into a lake is unclear. The Lava Creek B tephra was probably deposited in a lake because it contains small-scale cross beds, the upper contact between the tephra and lake sediment is conformable, and the sediments that over-lying it closely resemble the other lake sediments: tan to brown, carbonate-rich silt and sand. The paleosol that is developed into the sediments directly above the Lava Creek B tephra, and into the tephra itself, is indicative of a lake-level recession relatively soon after the tephra erupted.

Site 4

**Description.** Site 4 (Figs. 8 and 13), like Site 1, is situated in a scarp of the Lake Thatcher terrace, 30 m below the highest shoreline. Site 4 exposes a delta formed into Lake Thatcher at the mouth of Smith Creek. The upper (4 m) sediments are exposed in the head scarp of a landslide, whereas the other three exposures (1.5 to 4 m high) are several meters downhill.

Unlike Sites 1 through 3, whose beds generally alternate between tan/brown to white silt and fine sand interbedded with organic-rich beds, only ~1 m (1,627 to 1,628 m asl) of Site 4 has similar characteristics. The upper 6 m of Site 4 are predominantly composed of laterally continuous, poorly sorted, cobbly gravel; only two other beds (<10 cm thick) in sections 1a and 3c contain sediments nearly as coarse. The lowest 3 m are composed entirely of finely laminated red clay, unlike any other I found elsewhere in the Main Canyon Formation (Fig. 19).

Similar to the other sites described in this study, the exposures at Site 4 contain a paleosol and a tephra. A paleosol that includes an organic-rich A horizon (<10 cm) and a <1-m-thick $B_w$ horizon is developed into the upper 1 m of the exposure. With the
Figure 19. Basal 3.5 m of red/brown clay, containing *Sphaerium* with paired valves, at Site 4 in Thatcher Basin, Idaho. The surface of the uppermost bed visible in this picture is an unconformity.
exception of an A horizon, this paleosol has similar properties to the one developed into the upper 1 m of section 1a: it is structureless, oxidized, and has calcium carbonate accumulation, especially noticeable on the underside of the cobbles. A 6-cm-thick, fine-grained, white tephra (AH95-8k) was found at 1,627 m asl, beneath a densely fossiliferous shell bed (Table 12, Fig. 20). This tephra correlates with the proto Mount St. Helens tephra collected at section 1d. The bounding contacts of the tephra are conformable with the adjacent beds.

No shells were found in the upper half of the exposure at Site 4, but the lower half contains at least five genera of molluscs. The basal 3 m of Site 4, composed entirely of red clay, contain organic debris and whole *Sphaerium* with paired valves (Fig. 19). Within the clay, at ~1,625 m asl, a silty bed with an erosional upper contact was uncovered. Its surface was scarred with pits that measured ~1-3 cm in diameter. *Sphaerium*, whose shells were extremely fragile and paper thin, were collected from the base of the depressions, which were infilled with clay from the overlying bed. A fossil-

Figure 20. Proto Mount St. Helens tephra interbedded with silt (above) and sand (below) at Site 4 in Thatcher Basin, Idaho.
Rich bed at 1,628 m asl is laterally continuous with a bed containing similar genera of molluscs ~30 m to the east. Four genera of molluscs, whose shells were well preserved, were collected from the two beds.

**Interpretation.** The beds in the lowest 6 m of Site 4 were most likely deposited in relatively quiet water owing to their fine grain size. *Valvata*, found in the fossiliferous layer at 1,628 m asl in the middle of the section, support this interpretation. The unconformity within the lowest 4 m of Site 4 probably represents a lake-level recession prior to the deposition of the proto Mount St. Helens tephra. The cobbles in the upper 6 m of Site 4 were deposited as topset beds by Smith Creek during the formation of a delta. Deposition of the coarse sediment in this high-energy environment probably prevented population by molluscs by creating an inhospitable environment. Similar to Site 1, the paleosol developed within the upper 1 m of gravel at Site 4 records a lake-level recession prior to lake-level rise, separating the two lake cycles represented at Site 4.

**GEOCHRONOLOGY**

A histogram of D/L ratios in all *Valvata*, the most prevalent fossil shell in Thatcher Basin, was plotted to assess the relative-age distribution of lake deposits (Fig. 21). Two clusters in D/L ratios (0.15-0.30 and 0.40-0.65) are evident. These clusters, termed "aminozones" (Nelson, 1978), represent periods of lacustrine sedimentation, whereas absence of D/L ratios is suggestive of periods of nondeposition during low lake level. The two aminozones in Lake Thatcher imply that either: (1) Thatcher Basin had two distinct lake episodes separated by a long interval of non-lake deposition or (2) deposits of intermediate age were not sampled.

The D/L ratios in shells collected from the Main Canyon Formation range from 0.11 (UAL-1591) to 0.74 (UAL-1402) (Table 13). At Sites 1 and 2, shells have D/L
ratios <0.3, with the youngest fossils (lowest D/L ratio) at the top of section 1a. Based on D/L ratios (0.19-0.46), and the relative position of the proto Mount St. Helens tephra, Site 4 spans more time than Sites 1 and 2 (Fig. 22). The D/L ratios at Site 3, which contains the Huckleberry Ridge and Lava Creek B tephra, range from 0.20 (UAL-1381) to 0.74 (UAL-1402). This site represents the greatest length of time, although deposition was not continuous: A gap in the D/L ratios, between 0.42 and 0.20, might represent a prolonged interval of nondeposition. The exact location of the unconformity is hidden by slumped deposits.

Figure 21. Frequency distribution of D/L measured in Valvata collected from Thatcher Basin, Idaho.
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Average C. V. 12
Figure 22. Stratigraphic columns measured at four sites in Thatcher Basin, Idaho (Fig. 8) arranged according to elevation. Lines connect beds of equal age based on the presence of tephra, paleosols, and D/L ratios. Elevation is in meters above sea level.
Lower Main Canyon Formation

Tephra, in conjunction with D/L ratios, provide limiting ages on the lower Main Canyon Formation. The Huckleberry Ridge ash places a maximum limiting age of 2.01 Ma on the overlying Lake Thatcher sediment at Site 3. Because of covered contacts and a limited supply of fossil shells at Site 3, it is uncertain whether the Huckleberry Ridge tephra was deposited in a lake (see Interpretation of Site 3 for details).

To assess the ages of the middle-Quaternary deposits of the Main Canyon Formation, the stratigraphic position of the Lava Creek B tephra was compared to the adjacent beds. No shells were found at the exposure that contains the Lava Creek B tephra, so elevation was used for correlation with beds that contained shells. The top of section 3c, which is ~9 m high, is 1 m below the base Lava Creek B tephra and contains Valvata, whose D/L ratios range from 0.74 to 0.42. The high D/L ratios are in agreement with McCoy's (1987a) D/L ratio of 0.70 in Valvata collected between the Huckleberry Ridge and Lava Creek B tephra at this site. Although the beds appear horizontal over hundreds of meters, and their elevation should be reliable for correlation, the possibility that the tephra is separated from the shell-bearing beds by a high-angle unconformity cannot be ruled out. On the other hand, the ratios are similar to those analyzed by McCoy (1987a) in shells collected in Little Valley ~5 m below the Lava Creek B tephra. McCoy measured a D/L ratio (D/L = 0.81) in Lymnaea (?) (analyzed in the autumn of 1980 when all samples yielded consistently high D/L ratios) collected at Little Valley, where the MAT is higher than in Thatcher Basin, enhancing the rate of racemization. This substantiates the assumption that the lowest ~28 m of Site 3, below the Lava Creek B tephra, are older than 620 ka, yet younger than 2.01 Ma.

An organic-rich bed 22 cm below the Rye Patch ash (630 ka) at Site 5, and organic-rich beds within 2 m below Lava Creek B tephra at Site 3d, suggest that lake
level was shallow prior to the eruption of these tephra. The dominance of *Valvata* throughout section 3d supports this interpretation. The 1 m of silt and sand deposited conformably above the Lava Creek tephra, into which a soil is formed, suggests that lake level was ~high after 620 ka for some time before lake level receded below 1,536 m asl.

**Upper Main Canyon Formation**

To date the upper-Quaternary lake deposits of Thatcher Basin, I calibrated the amino acid data using two independent ages: (1) the radiocarbon-dated chronology of Lake Bonneville (Oviatt and others, 1992) and (2) the correlated age of the proto Mount St. Helens tephra.

The first independent age used for calibrating the rate of racemization is the age of the most recent Lake Bonneville highstand. Obtaining D/L ratios to characterize deposits of the last rise of Lake Bonneville in Thatcher Basin is difficult because I did not find molluscs in Lake Bonneville sediments that were definitely not reworked from older deposits, although preliminary results by Dave Bouchard (Utah State University) suggest that *Lymnaea* with D/L ratios indicative of the most recent Lake Bonneville highstand are present in the southern part of the basin. Also, McCoy (1981) measured a D/L of 0.08 in *Valvata* in Thatcher Basin. For the purpose of the calibration curve, D/L ratios were measured in nine *Lymnaea* samples (1 to 3 shells per sample) from sediments of the most recent Lake Bonneville highstand (D/L = 0.09 ± 0.01) in northern Cache Valley (Table 14). Because Thatcher Basin is approximately 50 km north of northern Cache Valley, the temperature, and therefore the rate of racemization, is expected to be somewhat lower. The current mean annual temperature (MAT) at Grace, 19 km north of the town of Thatcher, is 5.9 °C and the MAT at Preston, in northern Cache Valley, is 7.4 °C (Donald Jensen, Utah State University, personal communication, 1995). Assuming that the
TABLE 14. D/L RATIOS IN LYMNAEA COLLECTED FROM NORTHERN CACHE VALLEY

<table>
<thead>
<tr>
<th>UAL #</th>
<th># shells</th>
<th>D/L</th>
<th>σ</th>
<th>Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1045</td>
<td>2</td>
<td>0.09</td>
<td>0.01</td>
<td>Kaufman/Hochberg</td>
</tr>
<tr>
<td>1110</td>
<td>3</td>
<td>0.08</td>
<td>0.02</td>
<td>Kaufman</td>
</tr>
<tr>
<td>1111</td>
<td>3</td>
<td>0.08</td>
<td>0.01</td>
<td>Kaufman</td>
</tr>
<tr>
<td>1370</td>
<td>1</td>
<td>0.08</td>
<td></td>
<td>Erickson</td>
</tr>
<tr>
<td>1422</td>
<td>3</td>
<td>0.08</td>
<td>0.01</td>
<td>Smith</td>
</tr>
<tr>
<td>1424</td>
<td>1</td>
<td>0.09</td>
<td></td>
<td>Smith</td>
</tr>
<tr>
<td>1428</td>
<td>1</td>
<td>0.11</td>
<td></td>
<td>Smith</td>
</tr>
<tr>
<td>1430</td>
<td>1</td>
<td>0.08</td>
<td></td>
<td>Smith</td>
</tr>
<tr>
<td>1431</td>
<td>1</td>
<td>0.10</td>
<td></td>
<td>Smith</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.09</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

The present temperature difference was the same as in the past, then the temperature difference between the two localities (1.5 °C) should have resulted in a slight difference in D/L ratios. The extent to which D/L in the Thatcher shells should be lower than in Cache Valley shells is difficult to estimate, but probably approximates the intershell variation (~10%). If this assumption is not entirely true, and the difference between the racemization rates in Cache Valley and Thatcher Basin is more extreme than anticipated, then the calibrated ages of the Main Canyon Formation would be slightly too young.

The age of the last Lake Bonneville highstand deposits in Cache Valley can be estimated using the radiocarbon-dated lake-level hydrograph of Oviatt and others (1992). Lake Bonneville entered Cache Valley ~25 ka, reached its maximum elevation 17-15 ka, and began a rapid decline at ~14 ka. Therefore, I estimate the age of the molluscs collected from sediments of the most recent Lake Bonneville highstand at 20 ± 5 ka.
The age of the proto Mount St. Helens ash is crucial to the late-Pleistocene Lake Thatcher lake-level chronology because it occurs within the youngest sediments of the Main Canyon Formation. The tephra was found at two sites in Thatcher Basin (1 and 4) separated by ~12 km. It is also known from two other places in the western U.S., and has been correlated with the tephra of the upper Main Canyon Formation by Andrei Sarna-Wojcicki (Table 15). The major-element composition of the tephra is 96% similar to an ash found by Cathy Whitlock (University of Oregon) in a sediment core from Carp Lake, Oregon, based on the average of three samples, and 94% similar to an ash found by Alan Busacca (affiliation) in loess from the Columbia Plateau, eastern Washington. Berger and Busacca (1995) dated loess 3 m above the ash at 83 ka by thermoluminescence. Based on the average loess accumulation rate during the past 80 ka, they suggest that the tephra is ~120 ka. In Carp Lake, the tephra overlies >3 m of lake sediment that contains pollen indicative of lower than modern temperature. Whitlock (personal communication, 1995) estimates the age of the ash at 50-75 ka, probably corresponding to marine oxygen-isotope stage 4. I averaged the two age estimates, arriving at an age of 90 ± 30 ka for the proto Mount St. Helens tephra.

Because the rate of racemization is taxon dependent, the D/L ratios used in the calibration curve must be measured in the same genus, or from genera with comparable racemization rates (see Chapter 2). The D/L ratio associated with the proto Mount St. Helens tephra is based on a sample collected closest to the tephra at section 1d where the average D/L ratio in Valvata collected 1.5 m above the tephra is 0.21 ± 0.01 (n = 3). At Site 4, the other proto Mount St. Helens tephra locality, the intershell variation in D/L ratios in Valvata <1 m above the tephra was higher (0.19 ± 0.03, n = 4) and, therefore they were not used. The lab-heating results (see Chapter 2) indicate that Valvata racemizes ~17% faster than Lymnaea. Therefore, for the purpose of calibration, D/L in
TABLE 15. COEFFICIENT OF SIMILARITY BETWEEN PROTO MOUNT ST. HELENS TEPHRA FOUND IN THATCHER BASIN AND CARP LAKE AND COLUMBIA PLATEAU

<table>
<thead>
<tr>
<th></th>
<th>CARP LAKE</th>
<th>COLUMBIA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CL-90A(1)</td>
<td>CL-90A(2)</td>
</tr>
<tr>
<td>AH95-3p (Site 1)</td>
<td>0.977</td>
<td>0.948</td>
</tr>
<tr>
<td>AH95-8k (Site 4)</td>
<td>0.979</td>
<td>0.951</td>
</tr>
</tbody>
</table>

Note: Mn and Na were not used for comparison because their concentrations were too low. Data from Sarna-Wojcicki, 1995, personal communication.

Valvata from section 1d was converted to D/L in Lymnaea using this relation, yielding 0.18 ± 0.01. No attempt was made to adjust the uncertainty associated with this D/L ratio according to the reliability of the intergeneric transformation.

The basic assumption of a kinetic model is constant temperature. Because fossil shells are invariably exposed to fluctuating temperatures, resulting from Pleistocene climate change, fossils of different ages have different EDTs; therefore, the rate of racemization is not expected to conform to a conventional first-order kinetic model (Fig. 23). Instead, I used an empirical fit to the data, one based on a parabolic kinetic model (Mitterer and Kriauskul, 1989) (Fig. 24). This model provides a close fit to the data, yielding an R² of 1.0. When the D/L ratios associated with the proto Mount St. Helens tephra, the last rise of Lake Bonneville, and a modern sample (D/L = 0.01) are plotted against the square root of age, linear regression yields the age equation for Lymnaea:

\[ t = (1764.65D/L - 17.56)^2 \] (3)
Figure 23. Relationship between age and D/L for fossil molluscs collected in the northern Bonneville Basin. Independent ages include *Lymnaea* (*D/L* = 0.09) collected from Lake Bonneville sediments dated at 20 ± 5 ka and *Lymnaea* (*D/L* = 0.18) converted from *Valvata*, using the relationships presented in Chapter 2, collected above the proto Mount St. Helens tephra (90 ± 10 ka).

where *t* is sample age in years. This equation can be used for other genera after adjusting their D/L ratios according to the relationships presented in Chapter 2. An envelope was constructed around the calibration curve by connecting the error bars about the control points.

**Age of the Uppermost Main Canyon Formation.** To estimate the age of the uppermost sediments of the Main Canyon Formation, D/L ratios in fossils collected from the uppermost ~1 m of section 1a (Fig. 13), directly below the top of the Lake Thatcher terrace (1,660 m asl), were applied to eq. 3. D/L in *Lymnaea* from section 1a (UAL-1591, -1618) averages 0.12 ± 0.01 (*n* = 2), and 0.18 ± 0.01 (*n* = 5) in *Sphaerium* (UAL-1352, -1046) (Table 13). To support these data, I compared the relationship between the fossil *Lymnaea* and *Sphaerium* with *Lymnaea* and *Sphaerium* analyzed in the
Figure 24. Amino acid calibration curve for Thatcher Basin, Idaho, providing the age of the top of the Main Canyon Formation. Linear regression provides the age equation for *Lymnaea*. Dotted lines connect error bars, enveloping the linear regression.
lab-heating experiment (see Chapter 2). When heated at 142 °C for 35.5 hr, D/L = 0.18 ± 0.01 in *Sphaerium* (UAL-1578C) and D/L = 0.13 ± 0.01 in *Lymnaea* (UAL-1579C) (Table 3). This offset in D/L is similar to the offset measured in the fossil *Lymnaea* and *Sphaerium* from section 1a. According to eq. 3, a D/L of 0.12 results in an age estimate of 38 ka. The uncertainty associated with the age is +10/-9 ka based on the width of the envelope at D/L = 0.12. A more conservative estimate of the uncertainty incorporates the ±0.01 uncertainty in D/L, resulting in an estimated age range of 58-24 ka.

The mean age (~40 ka) or older part of the age range (~60-40 ka) is considered more reasonable age estimates than the younger end of the age range for several reasons: (1) The D/L ratio in *Lymnaea* collected from sediment of the most recent Lake Bonneville highstand in Cache Valley (0.09 ± 0.01) is 25% lower than *Lymnaea* collected from the top of the Main Canyon Formation (0.12 ± 0.01). The difference in D/L ratios suggests that the 24 ka age for the top of the Main Canyon Formation is too similar to the 20 ± 5 ka age of the Lake Bonneville highstand; (2) the *Lymnaea* described above was collected from Cache Valley where the temperature is presently 1.5 °C higher than in Thatcher Basin. The D/L ratio of 0.09 ± 0.01 may be slightly too high for *Lymnaea* of the same age in Thatcher Basin; and (3) at the conclusion of this study, a date of 42,500 ± 1800 yr B.P. was obtained on a mollusc collected from the shell-rich bed within the upper meter of Site 1. This age is nonfinite and should therefore be considered a minimum estimate.

A noticeable oddity of the calibration curve is the fact that all three data points can be connected with a straight line; linear regression results in an R² of 1.0 using a parabolic kinetic model that assumes isothermal conditions. If the temperatures were higher during the past ~20 ka relative to 90-20 ka, then racemization rates should have been lower 90-20 ka and, consequently, not conform to a kinetic model. A possible explanation for this unexpected behavior may lie in geographical effects on thermal
history. According to this study, Thatcher Basin contained a lake during certain intervals between ~90 and 20 ka; submerged shells experience warmer temperatures than emerged shells (Miller and Brigham-Grette, 1989). Also, it is possible that the temperatures during the last interglaciation, 60-30 ka (oxygen-isotope stage 3), were similar to today in Thatcher Basin. These two factors may be responsible for equilibrating EDT for the length of time represented by the calibration curve.

Stratigraphic evidence suggests that the paleosol at the top of the Main Canyon Formation, at Sites 1a and 4, is of middle-Wisconsin (oxygen-isotope stage 3) age, <~90 ka, yet >~40 ka. This age supersedes the presumed last-interglacial age originally proposed by Hochberg and Kaufman (1995). The paleosol lies directly below the shell-rich layer near the top of section 1a, which has been dated at ~40 ka using amino acid geochronology. The paleosol lies elevationally above the proto Mount St. Helens tephra collected from section 1d, dated at 90 ± 30 ka, found since the 1995 publication (Hochberg and Kaufman). Because Site 1 is a delta exposed by a roadcut, where the sections are separated by several meters in distance and elevation, I used aminostatigraphy to confirm the relative stratigraphic positions of the sections: the D/L ratios of section 1d are greater than those at section 1a. Thus, the paleosol at section 1a is younger than 90 ± 30 ka, suggesting that lake level fell below 1,659 m asl during this soil-forming interval.

**Age of the Main Canyon Formation Below the Highest Paleosol.** The length of time that Lake Thatcher filled its basin during the late Pleistocene can be estimated using the D/L ratios measured in shells at Sites 1 and 4, along with eq. 3. The two most prevalent genera at both sites are *Sphaerium* and *Valvata*. The average coefficients of variation for D/L ratios in these two genera, collected below the highest paleosol are 6% (n = number of samples = 4) and 12% (n = 7), respectively (Table 16).
### TABLE 16. COEFFICIENT OF VARIATION FOR SPHAERIUM AND VALVATA COLLECTED BELOW THE HIGHEST PALEOSOL OF THE MAIN CANYON FORMATION

<table>
<thead>
<tr>
<th>UAL #</th>
<th>Genera</th>
<th>Ave D/L</th>
<th>σ</th>
<th>Site #</th>
<th>Elevation (m asl)</th>
<th>C.V. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1434</td>
<td>Sphaerium</td>
<td>0.21</td>
<td>0.01</td>
<td>1a</td>
<td>1616</td>
<td>5</td>
</tr>
<tr>
<td>1586</td>
<td>Sphaerium</td>
<td>0.28</td>
<td>0.02</td>
<td>1c</td>
<td>1604</td>
<td>7</td>
</tr>
<tr>
<td>1448</td>
<td>Sphaerium</td>
<td>0.46</td>
<td>0.02</td>
<td>4</td>
<td>1625</td>
<td>4</td>
</tr>
<tr>
<td>1384</td>
<td>Sphaerium</td>
<td>0.36</td>
<td>0.02</td>
<td>4</td>
<td>1623</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average C.V.</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>1404</td>
<td>Valvata</td>
<td>0.24</td>
<td>0.01</td>
<td>1c</td>
<td>1607</td>
<td>4</td>
</tr>
<tr>
<td>1396, 1584</td>
<td>Valvata</td>
<td>0.18</td>
<td>0.04</td>
<td>1c</td>
<td>1605</td>
<td>22</td>
</tr>
<tr>
<td>1432, 1583</td>
<td>Valvata</td>
<td>0.21</td>
<td>0.01</td>
<td>1c</td>
<td>1605</td>
<td>5</td>
</tr>
<tr>
<td>1403, 1587</td>
<td>Valvata</td>
<td>0.21</td>
<td>0.04</td>
<td>1d</td>
<td>1600</td>
<td>19</td>
</tr>
<tr>
<td>1449</td>
<td>Valvata</td>
<td>0.21</td>
<td>0.01</td>
<td>1d</td>
<td>1600</td>
<td>5</td>
</tr>
<tr>
<td>1397</td>
<td>Valvata</td>
<td>0.19</td>
<td>0.03</td>
<td>4</td>
<td>1628</td>
<td>16</td>
</tr>
<tr>
<td>1440</td>
<td>Valvata</td>
<td>0.26</td>
<td>0.03</td>
<td>4</td>
<td>1628</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average C.V.</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

Because *Sphaerium* seems more reliable, it was used in eq. 3 by converting its D/L ratios to *Lymnaea* using the relationship presented in Chapter 2 and an analogue in the lab-heating experiment.

*Sphaerium* (UAL-1384) collected at 1,623 m asl, the lowest fossiliferous bed at either Sites 1 or 4, and therefore the oldest based on its position relative to the Mount St. Helens tephra, has an average D/L ratio of 0.36 ± 0.02. Although the overlying bed contains *Sphaerium* with a higher D/L ratio (UAL 1448, D/L = 0.46 ± 0.02), these shells were excluded because the surface from which they were collected is an erosional surface, making the D/L ratios suspect (see Stratigraphy section). According to the lab-heating experiment presented in Chapter 2 (Table 3), when D/L in *Sphaerium* is 0.37 ±
0.01, D/L in *Lymnaea* is 0.20 ± 0.01. Plotting D/L = 0.20 on the calibration curve places a conservative maximum limiting age on the initial late-Pleistocene highstand of Lake Thatcher at ~110 ka.

The highest, and therefore youngest fossiliferous bed at either Site 1 or Site 4 below the highest paleosol, is at 1,616 m asl. *Sphaerium* collected from this bed has a D/L ratio of 0.21 ± 0.01 (UAL-1434). No analogue exists in the lab-heating experiments for *Sphaerium* with this D/L ratio, so the relationship (*Sphaerium* racemizes 26% faster than *Lymnaea*) presented in Chapter 2 (Table 6) was used to convert D/L in *Sphaerium* to D/L in *Lymnaea*. When D/L in *Sphaerium* is 0.21, D/L in *Lymnaea* is 0.17. According to the calibration curve, this places a minimum limiting age on the initial late-Pleistocene highstand of Lake Thatcher at ~80 ka. The relationship between the rates of racemization in *Sphaerium* and *Lymnaea* has much uncertainty inherent within it (see Chapter 2), so the limiting ages of the initial late-Pleistocene highstand should be heeded with caution.

**DISCUSSION**

**Effect of Bear River on Lakes Bonneville and Thatcher**

Because the history of basaltic activity in northern Thatcher Basin along the divide between the Pacific and Great Basin drainages is unclear, reconstructing the course of the Bear River during the Quaternary is difficult. Bright (1963) proposed that ancestral Bear River flowed westward through the Portneuf Gorge prior to being dammed by lava flows. According to this theory, the basalt flows altered drainage causing the Bear River to terminate in Thatcher Basin, forming Lake Thatcher (Fig. 7). He also suggested that, prior to the emplacement of the basalt, Thatcher Basin drained to the north. Bright’s model required that the elevation at the head of the Portneuf canyon was <1,458 m asl prior to basalt emplacement in order to have northward flow through Portneuf. But,
Mabey (1971) used gravity and well data to show that the base of basalt at the concealed divide at the head of the Portneuf River canyon is only 61 m below the surface, at 1,555 m asl. Based on geophysical evidence of a basalt-filled channel on the west side of Thatcher Basin that slopes to the south, Mabey (1971) contradicted Bright's hypothesis by proposing a pre-basalt southward drainage of Thatcher Basin. Several aspects of both models are flawed, however, because Bright believed that Lake Thatcher was in existence for <15,000 yr, when, in fact, it endured for several hundred thousand years, whereas Mabey never acknowledged the existence of Lake Thatcher.

A reconstruction that takes into consideration the evidence of Bright (1963) and Mabey (1971) is as follows: The Bear River did not flow into Lake Thatcher until after basalt filled the Portneuf River gorge and after the formation of a 1,684 m asl basalt divide between the Bear and Portneuf rivers. These flows diverted the Bear River southward into Thatcher Basin. The Bear River, at this time, carved a channel on the west side of the basin, recognized by Mabey (1971). For whatever reason, the Bear River migrated eastward to the center of the basin while Lake Thatcher filled. After Lake Thatcher overtopped the former divide at the south end of Thatcher Basin, the Bear River carved Oneida Narrows. With further lowering of base level, the Bear River commenced unimpeded flow into the Bonneville Basin and carved through the basalt at Black Canyon (Fig. 2).

Only two K/Ar dates on the basalts related to the diversion of the Bear River exist: (1) The basalt in Portneuf Valley is ~600 ka (Scott and others, 1982); and (2) several flows in Gem Valley average ~100 ka (Armstrong and others, 1975). The number of basalt flows in the Thatcher Basin vicinity, their extent, and their chronologic relationships are uncertain, as well as which specific flow(s) caused the diversion. The history of the volcanism is so uncertain that I hesitate to guess, based on the ages of the
basalt flows, when the Bear River was diverted into the basin.

The cause of the high lake levels in Thatcher Basin has yet to be fully ascertained. The added discharge from the Bear River and climatic change are both likely factors. It seems logical that, as first suggested by Bright (1963), the diversion of the Bear River into Thatcher Basin caused the overflow that led to the breaching of the divide at Oneida Narrows and unimpeded flow into the Bonneville Basin. It is also logical that climate played a role because during the ~1 Ma history of Lake Thatcher, climate was highly variable and closed lake basins often record climate change. Climate was probably most influential in causing lake-level fluctuations in Thatcher Basin prior to the diversion of the Bear River into Thatcher Basin, after which the added inflow of the Bear River was the leading factor.

**Correlations with Other Western U.S. Lakes**

To evaluate the possibility that climate change influenced the lake-level fluctuations in Thatcher Basin, its history was compared to that of other lakes in the Great Basin to identify regional similarities. Trends in high lake levels across the western U.S. may suggest an increase in precipitation or a decrease in evaporative loss, whereas low lake levels may be indicative of warm temperatures and high evaporative loss. When lake-level fluctuations in multiple basins in a particular region are synchronous, climate influence may be assumed. Assuming that synchronous lake-level fluctuations are a direct reflection of regional climate can be risky, however, without a careful evaluation of local geographical and geological conditions. For instance, Lake Tecopa existed prior to 2 Ma with several fluctuations in lake level until ~0.5 to 0.3 Ma when drying began (Reheis and others, 1993). Like Lake Tecopa, Lake Rennie in Fish Lake Valley, Nevada existed until 0.5 Ma, at which time it became ephemeral (Reheis and others, 1993). If the
history of each basin were not reviewed carefully, then it may appear that climate change caused the lake-level fluctuations. However, Lake Rennie is believed to have dried as the Sierra Nevada and White Mountains were uplifted, causing a rain-shadow effect, whereas Lake Tecopa dried after it breached its basin.

**Early-Middle Quaternary.** Direct comparison of early-Quaternary lake levels is difficult because each basin has a unique geologic history, dating methods lack precision, and exposures are few, but tephra can be used for direct correlation between lake basins. Sediments of a deep-lake episode deposited in Lake Lahontan are interbedded with the Rye Patch Dam and Lava Creek B tephra (see Morrison, 1991 for a review of early-Quaternary lake-level fluctuations in Bonneville, Lahontan, and Tecopa basins). The lake is thought to have dried shortly after 0.62 Ma as indicated by the development of paleosols into lake sediments above the tephra. Similarly, in the Bonneville Basin, the Lava Creek B tephra is interbedded with lake sediment and is also associated with two paleosols developed into the sediment directly above the tephra (McCoy, 1987a). Lake Tecopa sediment is also found interbedded with the Lava Creek B tephra, but the lake reportedly rose thereafter. This study documents the presence of a lake in Thatcher Basin during the early Quaternary, ~1 Ma through ~500 ka based on lake sediments also interbedded with the Lava Creek B and Rye Patch Dam tephra. A paleosol developed into the silt and sand that conformably overlies the Lava Creek B tephra signifies lake level recession soon after 620 ka. Thus, a lake existed in Thatcher, Bonneville, Lahontan, and Tecopa basins at 620 ka, based upon the presence of the Lava Creek B and Rye Patch Dam tephra interbedded with lake sediments. Lake level dropped in Thatcher, Bonneville, and Lahontan basins following the eruption of the Lava Creek B tephra as indicated by paleosol development.
Late Quaternary. Unlike Lake Thatcher, which was at or near its highest level at ~110-80 ka, inconclusive evidence suggests that lakes Bonneville, Searles, and Lahontan may have possibly been at moderate levels at this time, significantly below their late-Wisconsin (30-10 ka) maxima (Oviatt and McCoy, 1992). The Cutler Dam lake cycle in the Bonneville Basin, with a surface area less than half that of Lake Bonneville during its most recent highstand, is older than 36 ka, but substantially younger than deposits of the Little Valley lake cycle (~140 ka). The water table in Browns Room, a subterranean air-filled chamber of the Devils Hole fissure, Nevada was also at a moderate level, >5 m above modern between 116 and 53 ka (Szabo and others, 1994). Because Devils Hole is down gradient of a large (>12,000 km²) groundwater basin, it probably reflects regional climate conditions. Lake Manly in Death Valley was dry during Lake Thatcher’s initial late-Pleistocene highstand (Oviatt and McCoy, 1992), as was the Badwater salt pan (Lowenstein and others, 1995). Because Thatcher Basin is small (~260 km²) (Bright, 1963), especially in comparison to Lahontan (22,300 km²) and Bonneville (51,300 km²) (Benson and Thompson, 1987) basins, lake size may be more sensitive to climate fluctuations. Also, Lake Thatcher was at or near its threshold during its initial late-Pleistocene highstand and could rise no higher without overtopping its divide. This suggests that Lake Thatcher at its maximum level may be climatologically equivalent to moderate lake levels in larger basins. But whether lakes existed in Bonneville, Searles, and Lahontan basins between ~110-80 ka has not been ascertained. Inconclusive evidence cannot rule out the possibility that regional paleoclimate may have been the driving force behind lake-level fluctuations in Thatcher Basin, but the likelihood exists that there may have been another contributor, such as the diversion of the Bear River into the Bonneville Basin.
During its final rise at ~40 ka, Lake Thatcher was at or near its highest elevation while lake level in the Bonneville Basin may also have risen during the Cutler Dam lake cycle (Oviatt and others, 1987). Between 44 and 20 ka, the water table level in Browns Room fluctuated between +5 and +9 m and declined rapidly thereafter (Szabo and others, 1994). Therefore, Lake Thatcher, the water-table in Browns Room, and perhaps the Cutler Dam lake cycle in the Bonneville Basin were high during the middle Wisconsin. However, the uppermost paleosol of the Main Canyon Formation formed early in oxygen-isotope stage 3, implying that lake level was not high during the entire middle Wisconsin. The possibility remains that climate change was responsible for the high lake levels at this time, but this cannot be proven with certainty, suggesting that this highstand in Thatcher Basin may be attributed to the diversion of the Bear River into Thatcher Basin.

**Amino Acid Paleothermometry**

The amino acid data and the age estimate for the uppermost Main Canyon Formation were applied to a previously published equation (McCoy, 1981) that relates D/L in *Lymnaea* and time to temperature in an effort to determine paleotemperature. Assuming that the equation is accurate, the paleotemperature estimate will also indicate if the age (58-24 ka) assigned the D/L ratio (0.12) in *Lymnaea* collected from the uppermost Main Canyon Formation is reasonable.

\[
T^* = 6250/\left\{16.9-\log\left[\left(\ln\left((1+D/L)/(1-0.77D/L)\right)-0.0194\right)/(1.77t)\right]\right\}-273.16
\]

where \( T = \text{EDT (°C)} \).

This equation is based on a number of assumptions and uncertainties. The Arrhenius parameters (activation energy (\( E_a \)) and frequency factor (\( A \))) are the primary uncertainties, followed by the uncertainty in the independent age. In ideal situations, the
uncertainties lead to an overall ±2 °C uncertainty in the EDT.

The EDTs predicted for the range of age estimates (58-24 ka) for the uppermost Main Canyon Formation were evaluated using eq. 4, with D/L set at 0.12 ± 0.01, the youngest fossil collected from the Main Canyon Formation (Fig. 25). Using an age of 24 ka, the equation predicts an EDT between 7 and 8 °C; an age of 38 ka yields an EDT between 5 and 6 °C, whereas 58 ka yields an EDT of 3 °C. Because the MAT of Thatcher Basin is presently 5.9 °C, ages younger than ~40 ka yield temperatures higher than expected, considering that temperature must have been several degrees lower than

![Diagram](image)

**Figure 25.** The solution to McCoy's (1981) age/temperature equation for *Lymnaea*, depicting the relationship between age and effective diagenetic temperature (EDT) using the range of D/Ls measured in *Lymnaea* collected from the uppermost Main Canyon Formation.
present during a significant part of the shell's postdepositional history. Based on this information, either the younger half of the estimated age range is too young, or McCoy's (1981) temperature equation predicts EDTs that are too high. Based on the argument on p. 84 against an age as young as 26 ka, I prefer the former alternative. But a definitive conclusion regarding paleotemperature cannot be made until the age of the uppermost Main Canyon Formation and the temperature equation are better constrained.

**SUMMARY AND CONCLUSIONS**

The lake-level history of Thatcher Basin was interpreted by measuring stratigraphic sections and analyzing D/L in ~150 mollusc shells comprising 40 samples from four sites across the southern part of the basin. A local amino acid calibration curve was developed for *Lymnaea* using correlated ages of the proto Mount St. Helens tephra and the radiocarbon-dated sediment of the most recent Lake Bonneville highstand. D/L ratios in *Valvata*, *Sphaerium*, and *Amnicola* can also be converted to an age using the calibration curve and the intergeneric relationships presented in Chapter 2.

The Quaternary lake-level chronology of Thatcher Basin includes evidence for three lake episodes (Fig. 26). Between ~1 Ma and ~500 ka, lake level was low, but the possibility of high-water occurrences cannot be ruled out. A gap in the record exists between ~500 ka and ~110 ka, followed by two late Pleistocene highstands. The first highstand (I) lasted for at least 30,000 yr, and is separated from the final rise (II) by an interval of soil formation. Lake Thatcher II receded after the bedrock divide at Oneida Narrows was cut, allowing Lake Bonneville to back up into Thatcher Basin ~20 ka.

The timing of the three lake episodes in Thatcher Basin and an assessment of the paleoenvironments was determined using independently dated tephra and amino acid geochronology in conjunction with stratigraphy. Because the bounding contacts of the
Huckleberry Ridge tephra are covered, it could not be determined whether Lake Thatcher was present when the Huckleberry Ridge ash was deposited. High D/L ratios (0.5-0.7) in *Valvata* that were presumably collected from below the Lava Creek B tephra and above the Huckleberry Ridge tephra suggest that Lake Thatcher existed before 600 ka and probably as early as at least 1 Ma (Fig. 26). Between ~1 Ma until 620 ka, Lake Thatcher was shallow for much of the time as evidenced by six paleosols and 13 organic-rich silt and clay beds. No stratigraphic evidence for much of the middle Pleistocene (<600 ka) was located. In the late Pleistocene, Lake Thatcher existed at ~110 ka at or near its highest elevation (1,660 m asl) based upon an average D/L ratio (0.36 ± 0.02) in *Sphaerium* at Site 4 (UAL-1384) converted to D/L in *Lymnaea* using the relationships presented in Chapter 2, and then converted to age using eq. 3 (Fig. 24). This highstand (I) lasted until ~80 ka, based upon the D/L ratio (0.21 ± 0.01) in *Sphaerium* collected above the proto Mount St. Helens tephra at section 1b, and also converted to D/L in *Lymnaea*. A middle-Wisconsin paleosol separates this highstand from the final Lake Thatcher high-water episode (II), which occurred ~40 ka. The age of this highstand, represented by the uppermost Main Canyon Formation, is based upon the D/L ratio (0.12 ± 0.01) in *Lymnaea* interpolated along the calibration curve.

Lake Thatcher existed at 1,660 m asl for at least 30,000 yr between ~110 and ~80, but the possibility remains that Lake Thatcher existed at its highest elevation prior to ~110 ka during much of the middle Pleistocene. If deposits of intermediate age, between the highstand at ~1-0.5 Ma and the highstand at ~110-80 ka, were not sampled because they were not exposed, it would be erroneous to infer commencement of high lake level at ~110 ka.
Figure 26. Summary diagram of lake-level fluctuations in Thatcher Basin, Idaho. Dotted lines where uncertain. Numbers in brackets are D/L ratios; those for late Lake Thatcher were measured in *Lymnaea* and those for early Lake Thatcher were measured in *Valvata*. Horizontal bars represent the estimated duration that Lake Thatcher existed at its highest elevation given the uncertainty associated with the age estimation (25 to 15 ka based on Currey and Oviatt, 1985).
Important to note is the development of a paleosol separating the Lake Thatcher highstand at ~110-80 ka and ~40 ka. This may indicate very warm temperatures or temporary diversion of the Bear River out of Thatcher Basin. Because the Bear River contributes 565,800 acre-ft/yr of water (at the Oneida Narrows gaging station) (U.S. Department of the Interior, 1974) into Thatcher Basin, which is a very large volume when compared to basin size, it seems as if pedogenesis during warm weather is an unlikely scenario.

The extent to which lake-level fluctuations in Thatcher Basin can be attributed to climate or to other factors, such as the added input of the Bear River, is difficult to assess. During the eruption of the Lava Creek B tephra (620 ka), lakes existed not only in Thatcher Basin, but in Bonneville, Lahontan, and Tecopa basins as well (Morrison, 1991), suggesting that Lake Thatcher was in phase with regional climate. However, when Lake Thatcher was high ~110-80 ka, inconclusive evidence suggests that lakes Bonneville (Cutler Dam lake cycle), Lahontan, and Searles were possibly at moderate levels (Oviatt and others, 1987), unlike the water table level in Browns Room, which was higher than modern (Szabo and others, 1994). This highstand of Lake Thatcher may reflect the diversion of the Bear River into Thatcher Basin, causing the lake to fill to its threshold. A similar mechanism is proposed for Lake Thatcher's final highstand ~40 ka. Although the water table in Browns Room was higher than present (Szabo and others, 1994), and lake level (Cutler Dam) in the Bonneville Basin may have been at a moderate level (Oviatt and others, 1987), other lake basins in California and Nevada were dry at this time.

Bright (1963) claimed that the added discharge of the Bear River into Thatcher Basin would cause Thatcher Basin to fill in ~200 years. While at its threshold (~110 ka), three possibilities exist: (1) The Bear River began spilling over the divide at Oneida
Narrows into the Bonneville Basin; (2) the Bear River began spilling over a divide at the north end of the Thatcher Basin into the Pacific drainage basin; or (3) the Bear River was spilling to the north and south. Based on the fact that the bedrock gorge at Oneida Narrows was carved and that no channel has been identified in the north, I believe that Lake Thatcher spilled over its divide at the south end of the basin, allowing the Bear River to enter the Bonneville Basin (Fig. 27).

The influence of the Bear River on Lake Bonneville, however, is more difficult to discern. Qualitatively, if the Bear River was entering at \( \sim 110 \) ka, it took 90,000 years to fill Lake Bonneville to its all-time highstand. It seems unlikely that the Bear River was the driving force behind lake-level fluctuations; indeed, if the Bear River was entering at \( \sim 110 \) ka, the dessication events depicted on McCoy's (1987a) model are hard to explain (Fig. 6). The Bear River, owing to its large discharge, undoubtedly played a role in influencing lake-level fluctuations in the Bonneville Basin, but climate probably played a far greater role than the river itself. The entry of the Bear River into the Bonneville Basin at least \( \sim 110 \) ka by spillover is contrary to Bright's (1963) claim that the initial entry of the Bear River into the Bonneville Basin was as a through-flowing river at 27.5 ka, after the cutting of Oneida Narrows (Fig. 27).

With time, headward erosion narrowed the divide at Oneida Narrows, as proposed by Bright (1963). During the final highstand (\( \sim 40 \) ka), the lake spillover eroded through the divide carving Oneida Narrows, dropping lake level. As Lake Thatcher drained, the Bear River entered the Bonneville Basin as a through-flowing river at least several thousand years before Lake Bonneville rose to 1,555 m asl and backed up through Oneida Narrows into Thatcher Basin <20 ka (Oviatt and others, 1992).
Figure 27. Generalized Lake Thatcher and Lake Bonneville history in Thatcher Basin, Idaho as determined by this study. See Figure 7 for a depiction of Thatcher Basin history as determined by Bright (1963).
Future study should concentrate in Oneida Narrows and downstream, looking for flood deposits and erosional features to determine the peak discharge of the flow out of the gorge. This will provide insight as to how rapidly the Bear River eroded Oneida Narrows and how rapidly lake level dropped in Thatcher Basin. To determine the course of ancestral Bear River and its impact on lake level in Thatcher Basin, future attention needs to be focused on the basalt flows in and around the basin. The number, ages, and spatial distribution of flows need to be determined. If the ages of the basalt flows along the course of the Bear River and at the mouth of Portneuf River Canyon coincide with a highstand of Lake Thatcher, then presumably the entry of the Bear River into Thatcher Basin contributed to its rise. If, on the other hand, the eruptions do not coincide with lake-level changes, then their influence on the course of the Bear River and consequently on the volume of Lake Thatcher is less direct. The pre-basalt elevation of the divide separating the Pacific and Great Basin drainages should be determined to assess the maximum elevation that Lake Thatcher could have attained prior to volcanic activity.
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