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The Bear River's History and Diversion: Constraints, Unsolved Problems, and Implications for the Lake Bonneville Record

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Chapter 2

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ABSTRACT

The shifting course of the Bear River has influenced the hydrologic balance of the Bonneville basin through time, including the magnitude of Lake Bonneville. This was first recognized by G.K. Gilbert and addressed in the early work of Robert Bright, who focused on the southeastern Idaho region of Gem Valley and Oneida Narrows. In this chapter, we summarize and evaluate existing knowledge from this region, present updated and new chronostratigraphic evidence for the Bear River's drainage history, and discuss implications for the Bonneville record as well as future research needs.

The Bear River in Plio-Pleistocene time joined the Snake River to the north by following the present-day Portneuf or Blackfoot drainages, with it likely joining the Portneuf River by middle Pleistocene time. An episode of volcanism in the Blackfoot-Gem Valley volcanic field, sparsely dated to ~100–50 ka, diverted the Bear River southward from where the Alexander shield volcano obstructed the river's path into Gem Valley. Previous chronostratigraphic and isotopic work on the Main Canyon Formation in southern Gem Valley indicates internal-basin sedimentation during the Quaternary, with a possible brief incursion of the Bear River ~140 ka. New evidence confirms that the Bear River's final diversion at 60–50 ka led to its integration into the Bonneville basin by spillover at a paleo-divide above present-day Oneida Narrows. This drove rapid incision before the rise of Lake Bonneville into the canyon and southern Gem Valley.

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Bear River diversion at 60–50 ka coincides with the end of the Cutler Dam lake cycle, at the onset of marine isotope stage 3. The Bear River subsequently contributed to the rise of Lake Bonneville, the highest pluvial lake known in the basin, culminating in the Bonneville flood. Key research questions include the prior path of the upper Bear River, dating and understanding the complex geologic relations within the Gem Valley-Blackfoot volcanic field, resolving evidence for possible earlier incursions of Bear River water into the Bonneville basin, and interpreting the sedimentology of the Main Canyon Formation.

Keywords: Bear River, Lake Bonneville, Drainage integration, Gem Valley, Paleohydrology

2.1 INTRODUCTION

Lake Bonneville was the largest pluvial lake in the Great Basin at the last glacial maximum, and its extent seems anomalously large (McCoy, 1987; Benson et al., 1990). Lake Bonneville had five times the volume of water of the next largest pluvial lake in western North America (Lake Lahontan) at its respective highest level (Karow and Hampel, 2010). Based on the lack of higher geomorphic markers and other lines of evidence (eg, Balch et al., 2005), Lake Bonneville was also larger than at least the three preceding pluvial lakes within its same basin. As Gilbert stated (1890, p. 94), "It marks the greatest expanse of the ancient lake…Above the Bonneville shoreline the whole aspect is that of the dry land." Perhaps most importantly, Lake Bonneville was the only one known to overflow its topographic threshold near Zenda, ~2.7 km north of Red Rock Pass (Gilbert, 1890), which enabled temporary external drainage and the catastrophic Bonneville flood. Indeed, we do not know how high Lake Bonneville would have reached if internal drainage had been retained. This contrasts with the Pleistocene record of alpine glaciation in the region, wherein moraines record the largest ice extent during the earlier Bull Lake glaciation (eg Munroe, 2005; Licciardi and Pierce, 2008), roughly at the time of the Little Valley lake cycle in the Bonneville basin. Regardless of how anomalous the size of Lake Bonneville was, researchers agree that the rise, fall, and extent of Lake Bonneville through time relates to climate change. Yet, studies sometime overlook that late Pleistocene drainage changes, especially the diversion of the Bear River that has the largest discharge of any river in the Great Basin, played a key role in the changing hydrologic balance of the system. Resolving the influence of drainage changes will foster a clearer understanding of each factor involved in the cyclic fluctuations of successive lake levels.

Gilbert (1890, pp. 218–219) recognized that the history of Lake Bonneville's shorelines is largely a story of the balance between water supply and evaporation, and also that the Bear River has been the most important and dynamic source of water. Key geographic relations occur where the Bear River swings north to the edge of the Great Basin divide, from the Uinta Mountains to Soda

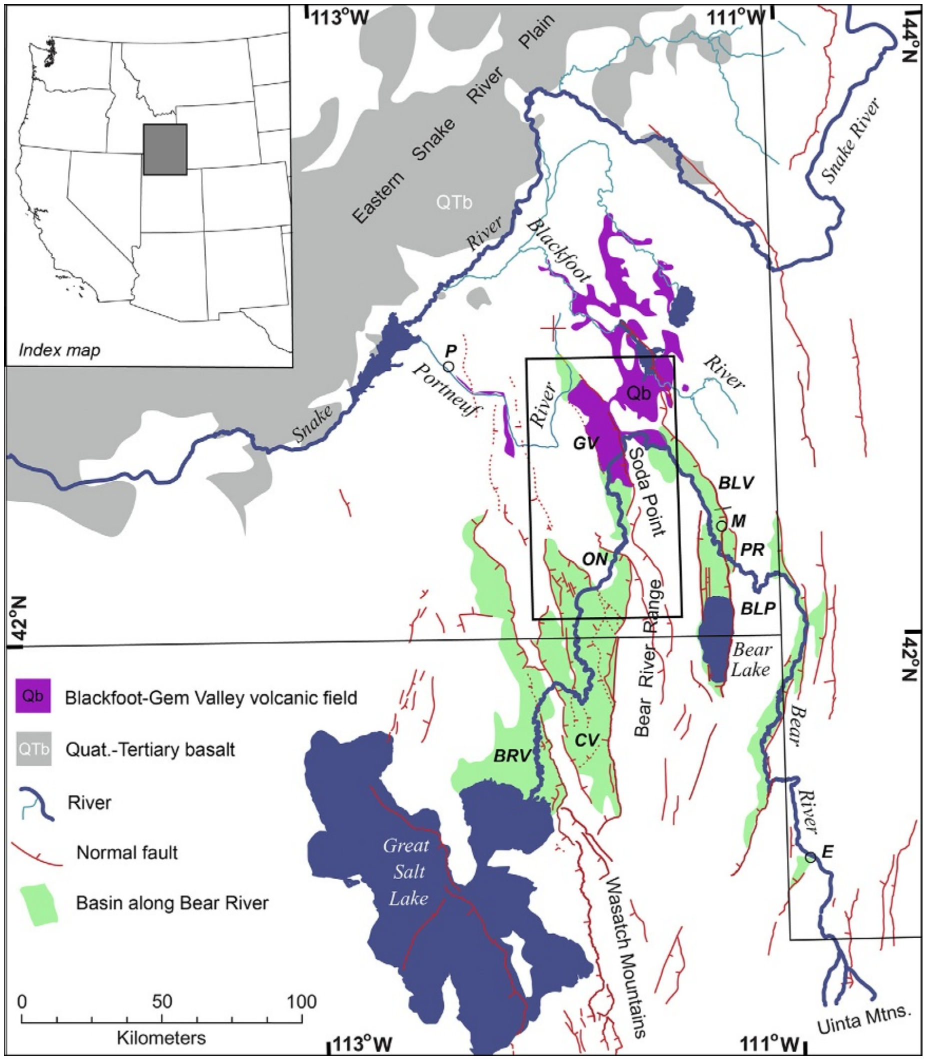

FIG. 2.1 Northeastern Bonneville basin and Bear River drainage region. *Rectangle outlines area* of Fig. 2.2. Key locations and features along the path of the Bear River are labeled: *E*, Evanston; *BLP*, Bear Lake Plateau; *PR*, Preuss Range; *M*, Montpelier; *BLV*, Bear Lake Valley; *GV*, Gem Valley; *P*, Pocatello; *ON*, Oneida Narrows; *CV*, Cache Valley; *BRV*, Bear River Valley.

Point, near Soda Springs, Idaho, between Bear Lake and Cache Valley, and then swings sharply south again (Fig. 2.1). Gilbert noted the very low divides between the Bear River and both the Portneuf and Blackfoot Rivers, both of which currently drain northwest to join the Snake River. He recognized that they and the Bear River may have been connected in earlier times, and perhaps were recently separated or diverted one way or another by the young basalt flows that built those drainage divides. Finally, in interpreting the overall hydrographic history of Lake Bonneville, Gilbert (1890, p. 263) explored the alternative hypothesis that rises and falls of the ancient lake might have been controlled by changes in the Bear River's drainage.

But Gilbert discussed how a former path of the Bear River to join the Snake River would have lowered lake level in the Bonneville basin, not whether recent diversion *into* the basin might have done the opposite.

Bright (1963) was the first to postulate that Lake Bonneville rose to its highest elevation of 1552 m partly in response to the first arrival of the Bear River into the Bonneville Basin. In fact, Bright grew up in the southeastern Idaho region in the middle of the geological records needed to test this hypothesis. His work, along with subsequent field and geochemical studies reviewed later, provide clear evidence that Pleistocene basalts erupted near the Bear River and eventually built a low divide across central Gem Valley in southeastern Idaho, thereby diverting the Bear River south from its connection to the Snake River basin into the Bonneville basin through the canyon of Oneida Narrows (Fig. 2.1; Bright, 1963; Bouchard et al., 1998; Link et al., 1999).

Our purpose in this chapter is to review the previous work in these key areas along the Bear River, present new results that help pinpoint the timing and mechanisms of this diversion, and discuss the implications for lake-level fluctuations in the Bonneville basin. We suggest future research that is needed to complete this understanding, including improved age control on basalt flows and sediments associated with the diversion of the Bear River, sedimentology of those same deposits, and investigation of possible earlier pathways of the upper Bear River.

2.2 SETTING AND EVOLUTION OF THE UPPER BEAR RIVER

The Bear River drains the northeast part of the Bonneville basin, which is itself at the northeastern corner of the Great Basin and formed as late Cenozoic extension created a set of closed basins inboard of the western North American plate margin. The Bonneville basin is fed largely by the Bear, Weber, Provo, and Sevier Rivers, which flow out of the Wasatch and western Uinta Mountains. The larger, modern-day Bear River drainage basin accounts for ~58% of the streamflow into the Bonneville basin (Tarboton, 2015). The 790-km-long Bear River exits the Bear Lake basin and turns west about half-way along its length southeast of Soda Springs, Idaho, there skirting the southern edge and eventually cutting through lava flows of the eastern (Blackfoot) portion of the Blackfoot-Gem Valley volcanic field (Fig. 2.1). Farther west, at a low divide across the center of Gem Valley built by basaltic cinder cones and lava flows, the river turns south and flows through the Black Canyon knickzone and southern Gem Valley (Fig. 2.2). Southern Gem Valley is also known in whole or in parts as Thatcher Basin, Gentile valley, and Mound valley (Bright's usage), but for clarity we will refer to Gem Valley as the entire structural basin and avoid these numerous local names. Farther south, the Bear River cuts through a low range between the main Portneuf and main Bear River Ranges, and enters the northern part of the Cache Valley graben through the ~300 m deep bedrock canyon of Oneida Narrows (Fig. 2.1).

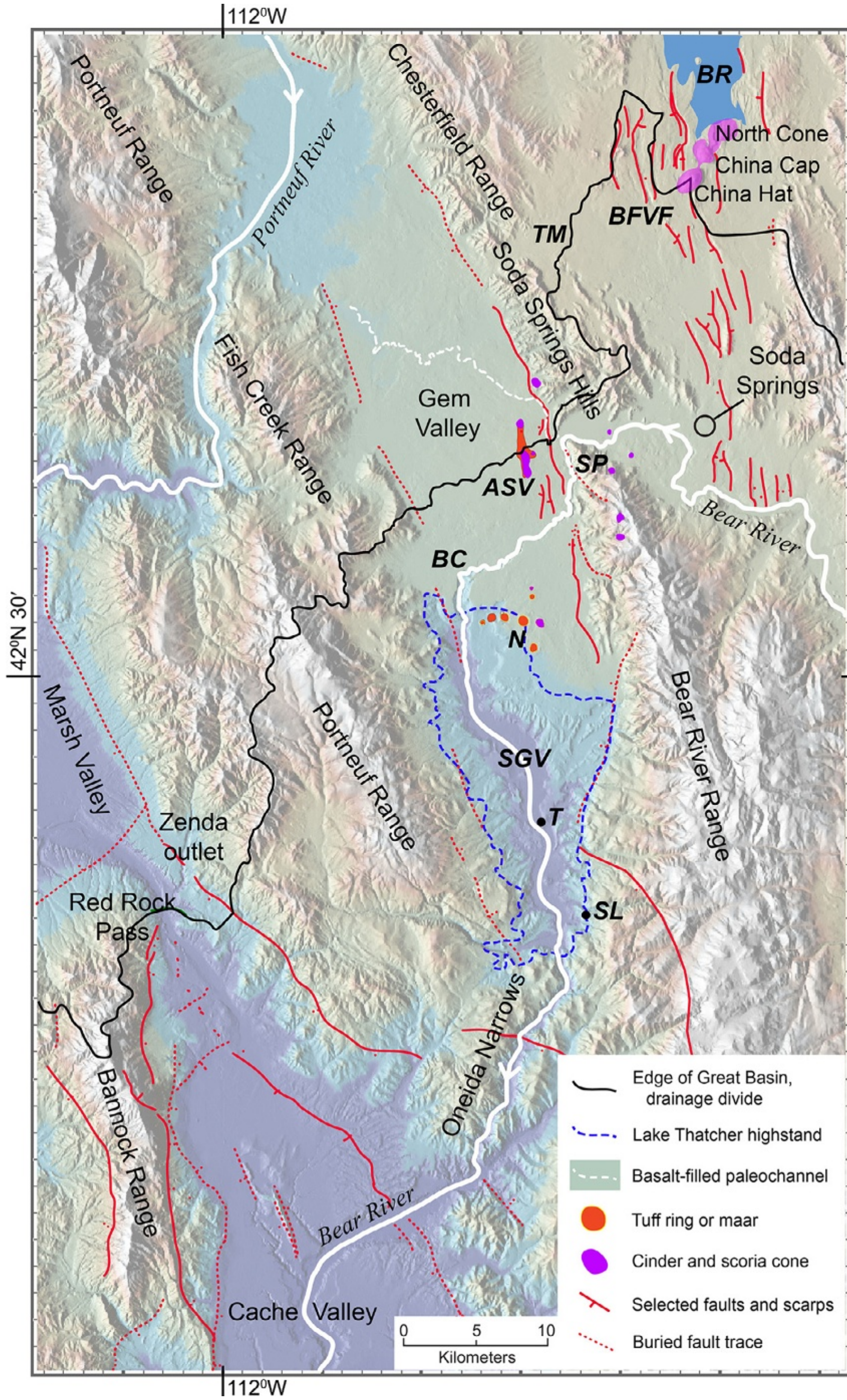

FIG. 2.2 Locations and features of the Gem Valley and Oneida Narrows area where the Bear River was diverted southward into the Bonneville basin. The highest shoreline of Lake Bonneville corresponds to the violet-to-blue transition of the background map at 1540 m, and the highest shoreline of Lake Thatcher is marked by the *dark blue dashed line* at 1660 m. *BR*, Blackfoot Reservoir; *BFVF*, Blackfoot volcanic field; *TM*, Tenmile shield volcano; *SP*, Soda Point; *ASV*, Alexander shield volcano; *BC*, Black Canyon; *N*, Niter cluster of volcanic vents; *SGV*, southern Gem Valley; *T*, Thatcher; *SL*, Smith locality of Fig. 2.4.

The geologic setting along this path of the Bear River is quite regular and systematic. From its headwaters in glaciated valleys on the north flank of the Uinta Mountains, the upper Bear River flows northwestward about 400 km (Fig. 2.1), stepping systematically westward through five east-tilted half grabens of the Basin and Range. The longest reach of the Bear River that cuts across the regional structural grain is northeast of Bear Lake, where the river crosses between the Bear Lake Plateau and the Preuss Range. After angling across Bear Lake Valley, the Bear River resumes a northward course as far as Soda Springs. The lower Bear River, downstream of Soda Point, changes to a southwest course, and from a left-stepping path to a right-stepping path through the extensional, mostly east-tilted basins of Gem Valley, Cache Valley, and Bear River Valley.

The integration of the upper Bear River is thought to postdate the Miocene-Pliocene Salt Lake Formation because that unit was deposited in basins of a significantly different landscape during early extension in the region (Janecke et al., 2003). The Salt Lake Formation is composed of tuffaceous and clastic lacustrine and fluvial sediments that have been distinctively tilted and folded by extensional structures (Evans and Oaks, 1996; Janecke and Evans, 1999; Janecke et al. 2003; Kruger et al., 2003; Long et al., 2006). Most of the Salt Lake Formation is 12–6 Ma, but uppermost conglomerates may be as young as ~3 Ma in some subbasins (Goessel et al., 1999; Oaks et al., 1999; Janecke et al., 2003; Keeley and Rodgers, 2015). The outward growth of the Basin and Range province documented by previous workers (Wernicke et al., 1987; Perkins et al., 1998) suggests that the undated exposures of the Salt Lake Formation along the NW-flowing, upper Bear River may be younger than those dated in basins to the west.

Early mappers (eg, Mansfield, 1927; Oriel and Platt, 1980; Taylor and Bright, 1987) interpreted the youngest sediments on the Bear Lake Plateau east of Bear Lake (Fig. 2.1) as Salt Lake Formation, and inferred that the Bear River was superimposed across structures there through a thick Miocene-Pliocene sedimentary fill. More recent geologic mapping has suggested that sedimentary rocks of the Salt Lake Formation are thin and fairly restricted areally on the Bear Lake Plateau (Coogan, 1992a,b, 1997a,b; Dover, 1995). This is pertinent because the oldest deposits mapped and interpreted as representing a through-flowing Bear River are preserved about 360 m above the river on the crest of the Bear Lake Plateau (Reheis, 2005; Fig. 2.1). Cross-bedded fluvial gravel and sand up to 5 m thick lie along a gentle north and east slope for at least 8 km along the drainage divide, toward the present Bear River. In one locality, nested channel fills show that this paleo-river incised as it migrated eastward (Reheis, 2005). These deposits are undated and are inset below the level of an Oligocene 28.8-Ma basaltic eruptive center (Coogan, 1997a). The gravels lack the distinctive pink and purple quartzite clasts derived from the Precambrian rocks of the Uinta Range, causing Reheis et al. (2009) to suggest that the earliest Bear River may have drained no farther south than about Evanston, Wyoming (Fig. 2.1), and only later captured its present headwaters, as previously suggested by Hansen (1985). An alternate possibility is that these high fluvial gravels predate the Bear River and are remnants of the Salt Lake Formation as mapped in the area by Coogan (1992a, appendix K), or perhaps they are both—earliest Bear River gravels in the uppermost Salt Lake Formation.

Evidence from terrace gravels and lacustrine deposits where the river enters Bear Lake Valley indicates that the upper Bear River was certainly integrated by late Pliocene to early Pleistocene time, after deposition of the youngest dated Salt Lake Formation (see Reheis et al., 2009, for details on the following relations). The highest terrace gravels mapped southeast of Montpelier, Idaho, are 80 m above the modern river, locally cap lacustrine deposits of a Plio-Pleistocene Bear Lake, and lie between two traces of the East Bear Lake Valley fault zone (Fig. 2.1). The second-highest river terrace in that area overlies several meters of fan-delta deposits, which in turn rest on deposits containing a tephra layer that is correlative with either the Bishop ash bed (765 ka; Zeeden et al., 2014) or upper Glass Mountain tephra (about 1 Ma; Sarna-Wojcicki, 2005).

Gilbert (1890) suggested that the low divides around Soda Springs and Gem Valley raise the possibility that the Blackfoot and Portneuf Rivers were once tributaries to the Bear River. He also briefly discussed the possibility, more pertinent here, that the Bear River once exited from Soda Springs through northwestern Gem Valley and then via the Portneuf River rather than southwest along its present course (Figs. 2.1 and 2.2). This Portneuf connection has been supported by geologic evidence (eg, Bright, 1963; Mabey, 1971; Janecke and Oaks, 2014). For example, Ludlum (1943), Bright (1963, 1967), and Scott et al. (1982) recognized that a pair of basalt flows follow a sinuous path westward and then southward down the Portneuf Valley from the Blackfoot-Gem Valley volcanic field. In addition, the Portneuf River appears underfit for its valley where it crosses through the Portneuf and Bannock ranges, supporting a paleo-Bear River addition to its discharge. More recently, Janecke and Oaks (2014) reported a separate basalt-filled meandering channel >4 km long, which trends west through central and west-central Gem Valley (thin dotted line in Fig. 2.2). Its east end projects to the modern Bear River at Soda Point, and the west end projects to the modern Portneuf River along the northwest margin of Gem Valley. Thus it may represent a basalt-filled channel of the paleo-lower Bear River. These lines of evidence strongly suggest that, at least during the middle to late Pleistocene, the paleo-Bear River flowed through northern Gem Valley and joined the Portneuf River to flow into the Snake River.

An older Plio-Pleistocene course directly north to the Snake River via the Blackfoot River cannot be ruled out, however. The modern divide between the Bear and Blackfoot drainages lies southeast of China Hat (Fig. 2.2) and is about 120 m above the Bear River near Soda Springs. Terrace remnants up to 40 m above the Bear River are recorded south of Soda Springs on the eastern, hanging-wall block of a normal fault (Reheis et al., 2009). If Quaternary volcanism resulted in 80 m or more of fill across the divide area, it is permissible that the river could have flowed north to the Blackfoot River during the early Pleistocene. In support of this, Mabey and Oriel (1970) indicated ~240–300 m of basalt in the area east of China Hat based on well and gravity data. However, fluvial gravels that might represent such a Bear River course have not been observed in a geothermal well drilled near Blackfoot Reservoir (eg, McCurry et al., 2011; Welhan et al., 2013), or along the lower valley of the Blackfoot River (Mansfield, 1929; Hladky et al., 1992).

Regardless of the exact pathway, the prior connection of the upper Bear River to the Snake River drainage is supported by consistent evidence from several species of organisms with aquatic biological affinity between the two basins (Taylor and Bright, 1987; Hershler and Sada, 2002; Smith et al., 2002; Mock et al 2006; Billman et al., 2010). However, the biological evidence does not accurately constrain the timing of aquatic connections or the location of the transfer. Miocene and Pliocene fossils of fish and molluscs provide general evidence of prior connections during these periods (Taylor and Bright, 1987; Smith et al., 2002), but former drainage patterns interpreted from fish do not always agree with those from molluscs. Distributions of several living species of fish in the Snake River and northern Bonneville-Bear River areas demonstrate interbasin transfers in the past, likely in both directions (eg, Minckley et al., 1986; Smith et al., 2002). In contrast to evidence from fish species, Taylor and Bright (1987) interpreted low endemism and a lack of obvious Snake River-related molluscs in the Bear Lake area to indicate that the lake was internally drained during the Pliocene and possibly not fed by an integrated Bear River until later.

Current research emphasizes the use of mitochondrial DNA (mtDNA) analysis to trace ancestry and vicariance among living species and to estimate time of divergence from geologic ages for related fossils, although estimated evolutionary rates vary among species (Smith et al., 2002). For example, the cutthroat trout, *Oncorhynchus clarki*, in the Bear River is estimated to have diverged from the upper Snake River population around 0.7 Ma based on mtDNA. However, these Bear River trout are more divergent from those in the main Bonneville basin, which suggests separate evolution during most of the Pleistocene. Similarly, *Lavinia* sp. (a cyprinid minnow) is reported from sediments thought to be about 6 Ma in both Cache Valley and north of Bear Lake, an age that supports a divergence time of ~6 Ma for the upper and lower Bear River as estimated independently from mtDNA evidence from living fish populations (Smith et al., 2002). The speckled dace (*Rhinichthys osculus*) is widespread in both the Bonneville and Snake River basins and occurs in two genetic groups corresponding to the southern Bonneville basin and the combined upper Snake River, northern Bonneville basin and the Bear River. The close similarity of populations in the northern group suggests fairly recent separation of the Bear and Snake River drainages (Billman et al., 2010). The same northern and southern division and similarity of Bear and Snake River populations exist in the Utah sucker (*Catostomus ardens*; Mock et al., 2006).

2.3 HISTORY OF FAULTING AND VOLCANISM IN GEM VALLEY

It is critical to understand the interplay of subsidence from normal faulting and volcanic constructional processes in Gem Valley because of its key role in diverting the Bear River to the Bonneville basin. The simple shape of Gem Valley itself contrasts with the geographic complexity of the five ranges along its margins (Figs. 2.1 and 2.2). Gem Valley basin is a structural graben ~2–3 km deep that lies on the southeast arm of the neotectonic parabola that is centered on the Yellowstone hot spot (Figs. 2.1 and 2.2; Pierce and Morgan, 1992; Piety et al., 1992). This graben is up to 70 km long, ~10 km wide, and is mostly filled by low-density sediments of the Miocene Starlight Formation and Miocene-Pliocene Salt Lake Formation (Mabey and Oriel, 1970). At most a few hundred meters of Quaternary sediment and basalt cap this thicker basin-fill sequence (Bright, 1963; Janecke and Oaks, 2014). The East Gem Valley fault zone has had enough activity to preserve fault scarps as high as 15 m across late Pleistocene basalt flows along at least 22 km of the central portion of its linear mountain front (Wong et al., 2012). A low slip rate of about 0.1 mm/year across the fault zone allowed two major breaks in the eastern mountain front to form at Tenmile Pass between the Chesterfield Range and Soda Springs Hills and along the Bear River between the Soda Springs Hills and Bear River Range. Lava flows entered Gem Valley from the Blackfoot field through both of these low points.

The bimodal, basalt-dominated, Quaternary Blackfoot-Gem Valley volcanic field is interpreted to have diverted the upper Bear River into its current southward route to the Bonneville basin in the middle to late Pleistocene (Bright, 1960, 1963, 1967; Bouchard et al., 1998). Tholeiitic porphyritic olivine basalt flows, cinder and spatter cones, and a small number of rhyolite domes erupted from a NNE-trending belt of ~100 discrete eruptive centers and fissures on the southeast margin of the eastern Snake River Plain (Mansfield, 1929; Oriel, 1968; Oriel and Platt, 1968, 1980; Armstrong, 1969; Perkins, 1979; Fiesinger et al., 1982; Pickett, 2004; Ford, 2005; Polun, 2011; Janecke and Oaks, 2014). Many of the basalt flows erupted from cones and fissures along N- to NNW-striking normal faults, fissures, and rift zones; the East Gem Valley fault zone, the Blackfoot rift zone, and the northern continuation of the East Bear Lake fault zone are among the most important conduits of the volcanic field (Oriel and Platt, 1968, 1980; Armstrong, 1969; Polun, 2011; Janecke and Oaks, 2014). Large-volume basaltic lavas flowed outward from these centers and produced a highly irregular map pattern of valley-filling basalt flows (Fig. 2.1; Lewis et al., 2012). Most of the volcanic rocks lie within a 250-km^2 rectangular area from central Gem Valley in the southwest to the Blackfoot Reservoir area in the northeast (Fig. 2.2), and far-travelled, valley-filling basalt flows, and satellite volcanic centers expand the outer edges of this volcanic field west to Pocatello, Idaho, and north to the margin of the eastern Snake River Plain (Mansfield, 1927; Ludlum, 1943, Bright, 1960, 1963, 1967; Oriel, 1965, 1968; Oriel and Platt, 1968, 1980; Armstrong, 1969; Fiesinger et al., 1982; Puchy, 1982; Coogan, 1992a; Pickett, 2004; Ford, 2005; Fig. 2.1).

The first K-Ar age determinations from the Blackfoot-Gem Valley volcanic field by Armstrong et al. (1975) yielded three whole-rock ages of ~100 ka on basalt flows in Gem Valley and three whole-rock and feldspar ages between 40 and 100 ka from the China Hat and China Cap rhyolite domes in the Blackfoot Reservoir area farther to the east (locations in Fig. 2.2). However, the analytical uncertainties were large and no tests were conducted to check for inherited Ar. In contrast, an older and reliable, whole-rock K-Ar age of 0.9 ± 0.2 Ma was determined by Armstrong et al. (1975) from a valley-filling basalt flow along the northern part of the Blackfoot River. This is the oldest dated basalt in the Blackfoot-Gem Valley volcanic field, with the early Pleistocene age supported by the reverse polarity (pre-0.781 Ma normal Bruhnes subchron) of other basalt flows in that northwest part of the Blackfoot-Gem Valley volcanic field (Mabey and Oriel, 1970).

Four subsequent $^{40}Ar/^{39}Ar$ and uranium-series dates from the volcanic field bring the early-to-late Pleistocene age of the volcanic field into better focus. A pair of stacked basalt flows known as the Portneuf (or Inkom) basalts were previously estimated by K-Ar to be ~140 ka (Armstrong et al., 1975) or ~600 ka (Scott et al., 1982), but a newer result of 430 ± 70 ka comes from a $^{40}Ar/^{39}Ar$ age on whole-rock from the lower lava (Rodgers et al., 2006). These two shoestring-like flows erupted from somewhere in the Blackfoot-Gem Valley volcanic field and flowed a minimum of 100 km west through canyons in the Portneuf and Bannock Ranges as well as across the Gem, Marsh and Portneuf valleys, reaching the south edge of Pocatello, Idaho (Figs. 2.1 and 2.2; Ludlum, 1943; Scott et al., 1982; Rodgers et al., 2006). These Portneuf basalt flows are the oldest yet dated in the Gem Valley part of the volcanic field.

The youngest basalt flows of the Gem Valley part of the volcanic field are late Pleistocene in age. This is based on a 90 ± 60 ka $^{40}Ar/^{39}Ar$ age on whole-rock from the Alexander scoria cone (Hughes and Pickett, in Pickett, 2004) at one of the subparallel fissures and rift zones at the center of the Alexander shield volcano. This cone lies 2.5 km north of the 1686-m divide that now separates the Columbia River drainage basin from the Bonneville basin (Fig. 2.2; Janecke and Oaks, 2014). Although there is a large uncertainty in the $^{40}Ar/^{39}Ar$ age determination arising from the low potassium content of all basalt flows in the field and this basalt's very young age, the 90 ± 60 ka age determination supports the late-middle to late Pleistocene ages inferred for many of the younger basalt flows nearby.

Volcanism to the east, in the Blackfoot part of the volcanic field, is better dated than in Gem Valley because the rhyolite domes there contain potassium-rich minerals (Fig. 2.2). Age control indicates that rhyolitic volcanism in the Blackfoot Reservoir area initiated between 2 and 1 Ma east of the Blackfoot Reservoir (Fig. 2.2; see summaries in Ford, 2005; McCurry and Welhan, 2012). At the youngest end, Pierce et al. (1982) redated the China Hat rhyolite dome to 61 ± 6 ka with the whole-rock K-Ar method. More recently the China Cap dome produced a 57 ± 8 ka $^{40}Ar/^{39}Ar$ crystallization age (Heumann, 1999), and uranium-series isochron dating of zircons provide an overlapping eruption age of 66 ± 7 ka from the same dome (Schmitt, 2011). Polun (2011) and Welhan et al. (2013) argued from all of these results that the genetically related rhyolite domes and maars in a NE alignment south of the Blackfoot Reservoir were erupted during a single episode. Altogether these geochronologic data suggest that basaltic and rhyolitic volcanism began together in the early Pleistocene and continued episodically into the late Pleistocene, ~100–50 ka.

2.3.1 Building of the Drainage Divide in Gem Valley

The Great Basin's drainage divide in Gem Valley has an irregular east-northeast trend across the Alexander shield volcano and a low point in the west at 1686 m (Fig. 2.2). The divide's surface, though covered with several meters of loess, preserves enough irregular topography to show that it is an original volcanic landscape that has not been modified by streamflow. The central part of Gem Valley has been paved over by basalts erupted from three volcanic centers. From north to south, these are the Tenmile (in the Blackfoot field), Alexander, and Niter clusters of volcanic vents (Fig. 2.2; Janecke and Oaks, 2014). The Alexander cluster of cinder cones and fissure vents, dated to 90 ± 60 ka (Pickett, 2004), in particular, may have built the current drainage divide across Gem Valley and thus eventually diverted the Bear River, as it appears to have erupted across the path of the river where it enters the east side of Gem Valley (Janecke and Oaks, 2014). In addition, a far-travelled flow from the Tenmile cluster of volcanic vents might have issued west through Tenmile Pass (Fig. 2.2), across northern Gem Valley, and played a role in confining or diverting the paleo-Bear River. Ongoing research in the volcanic rocks of Gem Valley may reveal the specific vent and basalt flow that diverted the Bear River southward.

The Niter volcano cluster is the southernmost cluster in the Blackfoot-Gem Valley volcanic field (Fig. 2.2). It is unusual in that it consists mostly of a half-dozen explosive phreatomagmatic maars and tuff rings, rather than cinder and scoria cones (Armstrong, 1969; Janecke and Oaks, 2014). The maars near the Bear River on the west side of this cluster give way eastward to tuff cones and finally to two cinder cones at higher elevations. The altitude of this transition between water-associated maars and normal cinder cones largely coincides with the ~1660-m highest shorelines of Lake Thatcher (Janecke and Oaks, 2014). Bright (1963) earlier documented pillow basalts nearby at this altitude. These phreatomagmatic maars and tuff rings suggest that most of the Niter cluster erupted when Lake Thatcher was at its highest levels. However, the westernmost two of these eruptive centers must have persisted somewhat longer because its low-relief ejecta ring lies in a lower, inset landscape position along the incised portion of southern Gem Valley, in association with basalt-capped terraces along the Bear River (Kackley and undifferentiated flows of Bright (1963) and Janecke and Oaks (2014)). This field relationship requires eruption of this westernmost maar after some of the incision of Oneida Narrows and southern Gem Valley, and thereby, the Bear River's integration south into the Bonneville basin.

2.4 CHRONOSTRATIGRAPHY OF SOUTHERN GEM VALLEY AND ONEIDA NARROWS

2.4.1 Prior Chronostratigraphy

The Pleistocene Main Canyon Formation constitutes the basin-fill record exposed in southern Gem Valley, and it provides critical information on the history of sedimentation and hydrology. The unit was first investigated in terms of stratigraphy and paleontology by Bright (1963, 1967). McCoy (1987), Hochberg (1996), and Bouchard et al. (1998) subsequently provided geochronologic and Sr-isotopic constraints as well as additional stratigraphic insights. Although detailed sedimentological work has yet to be done on the Main Canyon Formation, Bright (1963) interpreted it as Pleistocene sediments from local drainages with coarser alluvial fan sediments at the basin margins shed toward a fluctuating axial lake system with shorelines as high as 1660 m. A paleosol separates the lower and upper subunits of the ~150 m of exposed Pleistocene basin fill of the Main Canyon Formation (Hochberg, 1996). Bright (1963) and Hochberg (1996) interpreted the lower subunit as marshy and/or paludal sediments with numerous paleosols, and although the upper subunit is somewhat less organic-rich, it is still dominated by laminated to structureless silty sediment with numerous mollusc shells of lacustrine affinity.

Near its exposed base, the lower subunit contains the ~2 Ma Huckleberry Ridge tephra and the Lava Creek B tephra, the latter at 1535 m (~640 ka) (Izett, 1981; Hochberg, 1996; Bouchard et al., 1998; Lanphere et al., 2002). Hochberg (1996) discovered that the upper Main Canyon subunit includes beds geochemically correlated with an early Mt. St. Helens tephra, from a base at 1600 m and up to 28 m higher (Fig. 2.3). The tephra was first reported as ~110 ka (Bouchard et al., 1998), but it more broadly correlates with one of a series of early Mt. St. Helens tephra now thought to range from 120 to 70 ka (Kuehn and Negrini, 2010).

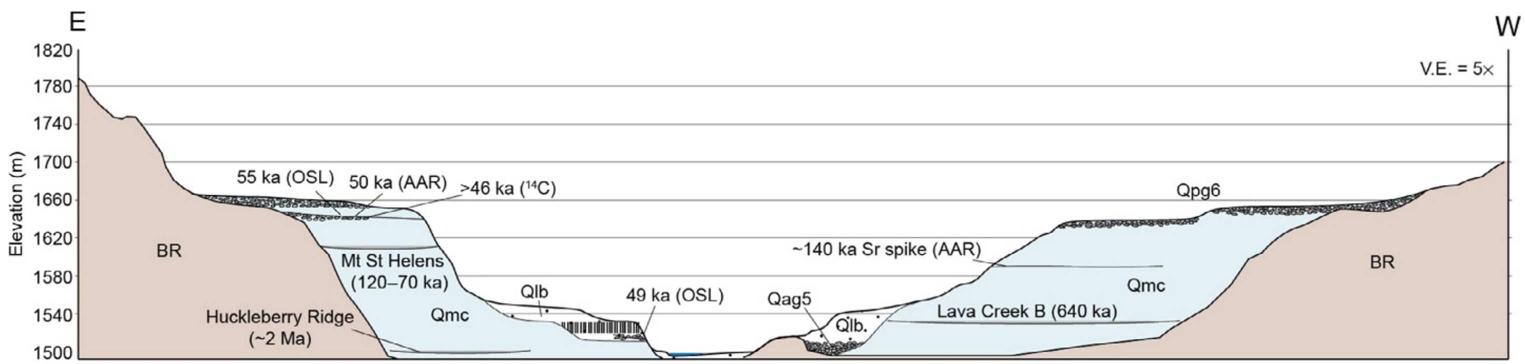

FIG. 2.3 Schematic cross section illustrating the chronostratigraphy of the Main Canyon Formation and other Quaternary deposits in southern Gem Valley, view looking south (downstream). *BR*, lower Paleozoic and Proterozoic sedimentary bedrock, *Qmc*, Quaternary Main Canyon Formation; *Qlb*, Quaternary sediment of Lake Bonneville overlying inset basalt flow (columnar hachures); *Qag5*, early-Bonneville-age channel gravel of the Bear River; *Qpg6*, late Pleistocene piedmont (alluvial fan) gravel capping the basin fill. The three corroborating ages by different methods (*AAR*, amino acid racemization) all come from the same marker near the top of the basin fill.

Initial work by Bright (1963, 1967) on the Main Canyon Formation included collection of a series of aquatic molluscs for radiocarbon dating, from near the exposed base to the top of the basin fill, ranging in age from 34 to 27 ka (uncalibrated radiocarbon years). In light of newer geochronology and given the potential for postdepositional isotopic exchange with shell carbonate, these are minimum ages, as recognized in McCoy's (1987) early work using aminostratigraphy. Regardless of knowledge of timing, Bright (1967) interpreted that, with the addition of water provided by the diverted Bear River into southern Thatcher Basin, spillover at the southern end through what is now Oneida Narrows fully integrated the Bear River into the Bonneville basin. Bright also recognized that subsequent incision of Oneida Narrows and southern Gem Valley by the Bear River was interrupted by the incursion of Lake Bonneville. This back-flooded the canyon and lower part of southern Gem Valley to the mouth of Black Canyon, north of the town of Thatcher (Fig. 2.2), and left fine-grained deltaic-lacustrine sediment lining the valley bottom.

Chronologic constraints indicate that sedimentation in the southern end of the Gem Valley graben either includes or proceeded after deposition of the 2-Ma Huckleberry Ridge ash and that sedimentation was episodic through deposition of the 640 ka Lava Creek B ash (Izett, 1981; Hochberg, 1996; Bouchard et al 1998). A maximum of ~150 m of dominantly fine, calcareous, organic-rich sediment accumulated at least through deposition of the 120–70 ka early Mount Saint Helens ash in the upper third of the Main Canyon Formation (Fig. 2.3). Average sediment accumulation rates in the Main Canyon Formation were very low, in part due to hiatuses represented by the multiple paleosols, and ranged from 0.07 to 0.20 mm/year for different parts of the sequence. These rates are a fraction of those calculated across similar timeframes from sediment cores drilled beneath the Great Salt Lake (0.38 mm/year; Davis, 1998) and Bear Lake (0.54 mm/year; Kaufman et al., 2009). Low sedimentation rates support the conclusion of Bouchard et al. (1998) that local streams provided the water and sediment for the bulk of the Main Canyon Formation. If the Bear River had been directly providing sediment for any extended period, its large discharge and sediment load would have resulted in a higher sediment accumulation rate as well as thicker, coarser, and redder-colored deposits.

2.4.2 History of Bear River Water Input to Southern Gem Valley

Bouchard et al. (1998) attempted to identify and date the arrival of Bear River water into the southern Gem Valley and its influence on deposition and the Main Canyon Formation through fingerprinting water sources by $^{87}Sr/^{86}Sr$ ratios. Two samples of Bear River water at Soda Springs yielded $^{87}Sr/^{86}Sr$ ratios of 0.70858 and 0.70922, varying seasonally, whereas the ratios from four local tributaries and a hot spring flowing into the southern Gem Valley were higher, ranging from 0.71037 to 0.71132. Because the Bear River has a discharge about twice that of the combined local sources, as estimated by Bouchard et al. (1998), they argued that its hydrologic contribution can be readily detected through relatively low $^{87}Sr/^{86}Sr$ ratios of mollusc shells found in the Main Canyon Formation. In the stratigraphically lowest and poorly exposed, early and middle Pleistocene part of this basin fill, they measured relatively high isotopic ratios (ave. = 0.71309) indicating no Bear River water entering the marshy setting of the basin. At the base of the upper Main Canyon Formation, stratigraphically between the ~640 ka Lava Creek B and the ~110 ka Mt. St. Helens tephra layers, Bouchard et al. (1998) reported a single mollusc sample with a lower $^{87}Sr/^{86}Sr$ ratio of 0.70987 and an amino acid racemization age of ~140 ka. They interpreted this lower Sr ratio as representing a first incursion of Bear River water into the basin, supported by Bright's (1963) suggestion that an interval of red sediment at that position in the basin fill is of Bear River provenance. Stratigraphically, this was followed by eight successively higher mollusc samples in the upper Main Canyon Formation, all with higher $^{87}Sr/^{86}Sr$ ratios indicative of internal drainage. At the top of the formation, they documented an isotopic shift in shell composition corresponding to a facies change, which they interpreted as the abrupt transgression of a larger lake caused by southward diversion of the Bear River. Bouchard et al. (1998) more specifically dated the final incursion of the Bear River based on shells in the same horizon as the isotopic shift by a minimum-accelerator mass spectrometry (AMS) radiocarbon date of 42.5 ± 1.5 cal ka (now recalibrated to 45.9 ± 2.8 cal ka utilizing; Reimer et al., 2013) and 50 ± 10 ka based upon amino acid dating (Table 2.1). Note that these were sampled at the same site as the ~27 ka radiocarbon date reported previously by Bright (1963).

It is worth building upon the hydrologic mass-balance calculations of Bouchard et al. (1998) to explore implications for paleohydrology. In addition to developing a mass-balance-and-mixing model to understand the sources and changes in their Sr isotopes, they pointed out that, even without a Bear River contribution, the local drainages and springs should have provided enough water to fill the southern Gem Valley basin over the timescale of centuries, and seemingly should have caused southward spillover (based on present-day discharges and evaporation rates). However, before construction of the volcanic divide separating northern and southern Gem Valley, presently at an altitude of 1686 m, any surface water may have joined the Bear River on a northern pathway out of Gem Valley. More importantly, groundwater would have found its own pathway downgradient through permeable basalts, either following the paleo-river's course northwest out of the basin, or flowing into the equally close Bonneville basin (Cache Valley, Fig. 2.2) to the south. Regardless, groundwater exit helped keep Gem Valley only marshy for most of the Pleistocene, as the preliminary sedimentologic interpretations of the Main Canyon Formation suggest. With the diversion of Bear River water, the more-restricted late Pleistocene southern basin would have filled rapidly—but how rapidly? Taking the historical record of Bear River

TABLE 2.1 Geochronology of the Upper Main Canyon Formation and Subsequent Integration of the Bear River

Method	Study	Sample	Stratigraphic Position	Dose Rate (Gy/ky)[a]	De (Gy)[b]	Age (ka)
Amino acid	Bouchard et al. (1998)	Molluscs lower in MCF	Earlier Bear River incursion (Sr)			~140
Tephra correlation	Hochberg (1996)	Early Mt. St. Helens tephra	Central-upper Main Canyon Fm.			~120–70
Amino acid	Bouchard et al. (1998)	Molluscs in lag gravel	Upper MCF lake transgression			50 ± 10
AMS radiocarbon	Bouchard et al. (1998)	Molluscs in lag gravel	Upper MCF lake transgression			45.9 ± 2.8[c]
OSL[d]	New	USU-846, Smith locality	Upper MCF lake transgression	3.35 ± 0.17	184.07 ± 9.29	55.0 ± 5.6[e]
OSL	New	USU-941, Sant Road cut	Inset Bear River, advanced incision	2.10 ± 0.11	102.43 ± 20.34	48.9 ± 6.9

[a] *Dose rates calculated from elemental chemistry using the conversion factors of Guérin et al. (2011) and cosmic-ray contribution following Prescott and Hutton (1994).*
[b] *OSL equivalent dose errors reported at 2σ.*
[c] *Radiocarbon age calibrated with IntCal03, errors reported at 2σ.*
[d] *OSL analyses use standard single-aliquot regenerative protocol (Murray and Wintle, 2000), calculated from between 17 and 43 accepted aliquots using the central-age model of Galbraith et al. (1999).*
[e] *OSL ages incorporate random and systematic errors reported at 1σ.*

discharge from the USGS gaging station at Pescadero (between Bear Lake and Soda Springs) as a proxy (1922–2014), we can confirm Bouchard's estimate of $\sim 5 \times 10^8$ m^3/year of water delivered by the Bear River to Gem Valley. As an order-of-magnitude estimate, one can generously represent the maximum volume of southern Gem Valley, partly filled with Main Canyon Formation, as a disk 5 km in radius and 100 m deep. Excluding evaporation rates, which are an order of magnitude slower than water input to this surface (Bouchard et al., 1998), we find that the basin could have filled with water and started spilling over in less than ~15 years.

In summary, the Main Canyon Formation's key role in recording evidence about the Bear River's diversion is well established, though further work is needed. The work of McCoy (1987), Hochberg (1996), and Bouchard et al. (1998) has made it clear that the short-lived lake basin in southern Gem Valley envisioned by Bright (1963, 1967) was instead a long-lived depositional basin that persisted as long as 2 m/year, generally matching the timing known for the volcanic field along its northern edge. Furthermore, the Bear River was a minor or secondary factor in the deposition of the Main Canyon Formation in southern Gem Valley, most of which has high Sr-isotopic signatures for mollusc shells indicative of internal drainage with only a singular occurrence of the red sediment diagnostic of the Bear River. All workers agree that the top of the formation records the Bear River's diversion southward into southern Gem Valley and the transgression of the highest Lake Thatcher. This southern incursion of the Bear River rapidly led to the hydrologic overtopping of the southern margin of Gem Valley, into the Bonneville basin.

2.4.3 New Age Control in the Upper Main Canyon Formation and Overlying Units

New geochronologic constraints on the timing of drainage diversion and incision of the Bear River are provided by mapping and optically stimulated luminescence (OSL) geochronology of Quaternary deposits above, within, and below Oneida Narrows. Only new data most pertinent to the Bear River's diversion are presented here. In southern Gem Valley, an exposure of the uppermost basin-fill strata has been sampled (Fig. 2.4). Observations there support previous interpretations of the sedimentology, with a mollusc-rich horizon of gravel lag marking the transgression of a standing-water lake over subaerial alluvial fan deposits derived from the eastern margin of the basin, which contain a well-developed buried soil (Fig. 2.4). This gravel lag, locally at ~1655 m, is interpreted to correlate with the horizon linked by Bouchard et al. (1998) to the shift to a Bear River-influenced Sr-isotopic signal. A new OSL age from a sample of the overlying, well-laminated lacustrine sandy silt, taken just 4–8 cm above the lag gravel, is 55.0 ± 5.6 ka (Fig. 2.4, Table 2.1). This date is consistent with the previous amino acid date of 50 ± 10 ka and the minimum ~46 ka AMS radiocarbon date reported by Bouchard et al. (1998). At the new

FIG. 2.4 Key relations and new OSL age in uppermost Main Canyon Formation found at the Smith locality, named for the local landowner (Fig. 2.2). Alluvial fan deposits and a buried soil profile marked by calcic-horizon development (as highlighted by gradational band) are slightly truncated and buried by a mollusc-rich, pebbly lag interpreted to mark lake transgression, as previously dated elsewhere in the basin. The new age determination is from directly overlying, laminated sandy silt interpreted as lake deposits preserved just before incision by the integrated Bear River.

study site, the dated sediment is, in turn, overlain by 4–5 m of thin-to-medium, tabular-bedded silt with dispersed molluscs and isolated, small lenses of locally derived gravel, here interpreted as littoral lacustrine deposits of the highest Lake Thatcher. Our rough hydrologic balance estimate and this date for the Bear River's incursion into the southern Thatcher Basin suggest that the rise of Lake Thatcher, spillover, and integration across the paleo-divide in Oneida Narrows would have occurred in just a few years at ~55 ka.

A new constraint on the timing of subsequent incision through southern Gem Valley is provided by an OSL date from sediment inset and near the bottom of the valley. The deposit is cross-bedded, pebbly sand of the Bear River that includes basaltic grains, and it underlies a basalt flow that stands above, but flanks, the modern, incised valley bottom between the town of Thatcher and the mouth of Black Canyon (Figs. 2.2 and 2.3). Both the deposit of the Bear River at 1520 m elevation and the overlying basalt flow are inset against the tuffaceous, early-middle Pleistocene, lower Main Canyon Formation. An OSL sample from the sandy Bear River sediment yields an age of

48.9 ± 6.9 ka (Table 2.1). Different beds of this road-cut exposure were likely sampled for geochronology by both Bright (1963) and McCoy (1987), with uncertain and mixed results. The basaltic lava flow that appears to disturb and overlie the newly dated fluvial deposit extends upstream a short distance and downstream along the eastern flank of the valley. The lava flow is, in turn, buried by a mantle of fine-grained Lake Bonneville deposits. This OSL age confirms that base-level lowering and much of the valley incision were accomplished just a few thousand years after river integration, well before the initial rise of Lake Bonneville, ~30 ka (Oviatt, 2015). Furthermore, this provides evidence for volcanism at ~50 ka, which in this case flowed into the actively eroding valley. As proposed by previous workers (Bright, 1963; Oriel and Platt, 1980; Bouchard et al., 1998), southern Gem Valley as well as the ~15-km-long Oneida Narrows canyon downstream was incised rapidly, mostly before it was back-flooded by the rising waters of Lake Bonneville (Fig. 2.5).

Previous estimates for the rate of this canyon incision have been hampered by the broad geochronologic constraints and by assumptions about the paleogeography and incision processes. Using a reconstruction of paleotopography based upon surficial mapping of the Main Canyon Formation basin-fill top and piedmont surfaces graded to it in southern Gem Valley, Pederson and King (2011) identified a paleo-drainage divide at ~1675 m (Fig. 2.5). This is less than half-way downstream through the canyon, at about the same position that Bright (1963) estimated. Thus, the spillover at ~55 ka took advantage of a low paleotopographic drainage divide and occupied north–south-directed local catchments (defined by the reconstruction of the mapped Qpg6 piedmont-upland surface) that had already defined and eroded the upper elevations of Oneida Narrows (Fig. 2.5). Only the narrower, inner gorge of Oneida Narrows needed to be incised by the Bear River after integration, representing a vertical maximum of ~225 m at the paleo-divide. Since new geochronology indicates most incision was accomplished before ~49 ka, the time-averaged vertical incision rate was 2–4 cm/year, depending upon whether one uses the central OSL ages or their reported errors to define the episode. Yet, it is likely that the vertical rate instead decayed over time and that incision was accomplished by an upstream-propagating and distributed knickzone across the 8-km distance through the resistant Proterozoic and Paleozoic strata of upper Oneida Narrows (Fig. 2.5). The evidence reviewed above for an earlier incursion of the Bear River into southern Gem Valley raises the possibility that Bear River water may have filled and spilled over the paleo-divide at that time as well, perhaps accomplishing prior erosion to the ~1675 m divide that was overcome at ~55 ka. So far, stratigraphic or geomorphic evidence for such an earlier integration and erosion episode have not been found. The present-day knickzone of Black Canyon in central Gem Valley represents the current position of the upstream-propagating wave of incision that was initiated by the final integration of the Bear River through Oneida Narrows.

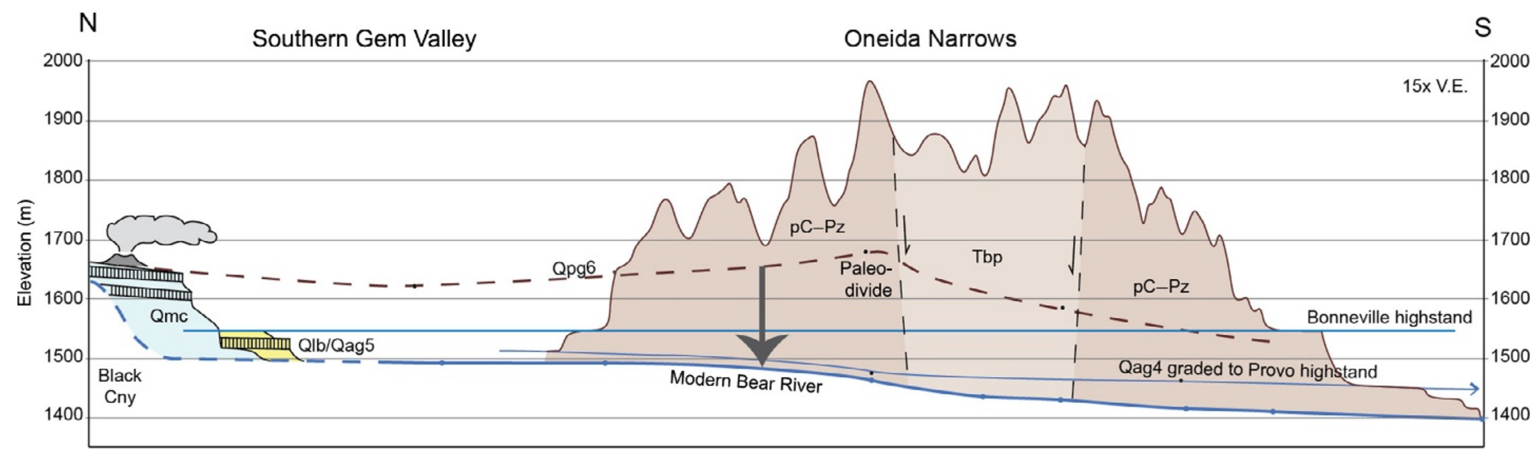

FIG. 2.5 Schematic longitudinal profile depicting geomorphic relations along the Bear River through southern Gem Valley and Oneida Narrows. Horizontal scale is shortened in Gem Valley to show relations. Qpg6 marks the reconstructed basin fill and paleo-drainage surface at the top of the Main Canyon Formation (Qmc), and Qlb/Qag5 are inset Bear River deposits, basalt flow (hachured columns), and Lake Bonneville deposits. Incision of Oneida Narrows through both Proterozoic/Paleozoic (pC–Pz) and Tertiary Salt Lake Formation (Tbp) bedrock below the reconstructed datum occurred rapidly; the propagating knickzone is currently located ~30 km upstream in Black Canyon.

2.5 PROXY EVIDENCE FROM THE BONNEVILLE BASIN

Although several paleoclimate and paleohydrologic reconstructions have been developed from the greater Bonneville basin, only two studies have interpretations regarding the history of the Bear River. First, as studied in the Main Canyon Formation, the input of the upper Bear River (above Oneida Narrows) may be detected by a shift in the Sr-isotope composition of carbonates formed in the terminal basin. Hart et al. (2004) interpreted the Sr-isotope values of lake water in the Bonneville basin as controlled by varying input from specifically the Bear River and Sevier River as well as from groundwater. They analyzed the $^{87}Sr/^{86}Sr$ value of molluscs from the primary shorelines of the Bonneville cycle and from the earlier Cutler Dam and Little Valley lake cycles and compared them to those of the modern Great Salt Lake. They found relatively low values in deposits of all lake cycles, generally tracking their magnitude, with Lake Bonneville deposits having the lowest value and the deposits of the Cutler Dam lake cycle and Currey's (1982) Gilbert shoreline having relatively higher Sr ratios. With their Sr-isotope mixing model, they tested for the effect of Bear River water, interpreting that the $^{87}Sr/^{86}Sr$ values measured in carbonates from all of the lake cycles are too low to have formed without input from the upper Bear River. This is partly consistent with Bouchard et al.'s (1998) Sr work reviewed above, in which one sample indicated the Bear River contributed water to southern Gem Valley during an earlier episode ~140 ka, potentially overflowing into the Bonneville basin at about the time of the Little Valley lake cycle. Yet, no incursion of Bear River water into Lake Thatcher was identified by Bouchard et al. (1998) at the time of the penultimate Cutler Dam lake cycle, which was dated by Kaufman et al. (2001) to 59 ± 5 ka, or during marine isotope stage (MIS) 4 (71–57 ka). The evidence described earlier indicates river integration just after this, in early MIS 3, yet the errors in numeric ages make it possible, strictly speaking, that Bear River integration and the Cutler Dam lake cycle overlapped in time. Lacustrine carbonates in the Bonneville basin older than the Little Valley lake cycle have not been analyzed for their Sr composition, and the $^{87}Sr/^{86}Sr$ values of molluscs in southern Gem Valley show that upper Bear River water was not a major contributor in the early and middle Pleistocene (Bouchard et al., 1998).

Davis (1998) and Davis and Moutoux (1998) analyzed the pollen content from drilled cores recovered around Great Salt Lake. They documented an abrupt increase in pollen concentration and sedimentation rate after 310 ka in the Indian Cove well, marking a change that they attributed to the initial diversion of the upper Bear River into the Bonneville basin. This does not match evidence from the Main Canyon Formation, which thus far indicates no influx of Bear River water or sediment into southern Gem Valley prior to about 140 ka. Age control in the Indian Cove core above the Lava Creek ash bed is by correlation of interglacial pollen assemblages with oddnumbered marine oxygen-isotope stages. Additional age control in the younger sequence in the Indian Cove core is needed to confidently assess the age of the transition to a higher sedimentation rate in the Bonneville basin, and more analysis is needed to determine if the increased sediment input can be ascribed to the Bear River vs a more local source.

2.6 DISCUSSION

2.6.1 Paleogeography and Diversion

Understanding the Pleistocene development of Gem Valley may be informed by taking a step back and considering the somewhat analogous relationships in the better-understood Bear Lake Basin ~75 km upstream. In both Gem Valley and Bear Lake Valley, the Bear River has either an antecedent or superimposed path west across the margin of an active structural basin, entering both north-trending valleys near their midpoints (Fig. 2.1). In Bear Lake Valley, the course of the river has alternated due to avulsion during the Quaternary between flowing: (1) south into the deeper subbasin of Bear Lake; (2) directly into the larger "open basin" area of maximum extent of the lake during glacial epochs (fig. 10 in Kaufman et al., 2009); and (3) along a route north of a smaller lake like the present one, and exiting the basin as it does today, when only man-made canals connect the river and lake (Robertson, 1978; Reheis, 2005; Kaufman et al., 2009). The path of the Bear River through Gem Valley during the early(?) to middle Pleistocene may have been broadly similar in map view to the modern Bear River in Bear Lake Valley. This analogy is consistent with other evidence that, for most of its history, the route of the Bear River was northwest across Gem Valley, toward the subsiding Snake River Plain, bypassing the depocenter on the south side of a growing divide created by flows from the Alexander shield volcano (Fig. 2.2).

Gem Valley contrasts with Bear Lake Valley in being less tectonically active and in having the coincidence of the Bear River entering the basin right where shield volcanoes and cinder cones were being constructed in the Pleistocene. No direct geologic evidence exists that an older "Lake Thatcher" ever occupied the northern part of Gem Valley, as Bright (1963, 1967) suggested, and instead the marshy sediments of the Main Canyon Formation are likely restricted to the southern basin. Due to the persistent presence of the Bear River, Pleistocene sedimentation rates in the southern Bear Lake Valley subbasin are significantly greater than in southern Gem Valley. The deposition of the lower and upper Main Canyon Formation was episodic, as indicated by paleosols, organic-rich intervals, and the significant unconformity that must lie between the basal Huckleberry Ridge Tuff (2 Ma) and the Lava Creek B ash (0.64 Ma) only 25 m above it (Hochberg, 1996). The slow accumulation rate is consistent with the conclusions of previous workers that only local catchments provided the water and sediment to the southern end of Gem Valley for the bulk of its history.

In Bear Lake Valley, groundwater connections exist between the river and Bear Lake even while surface water is disconnected. Likewise, during deposition of the Main Canyon Formation it is likely that a groundwater connection existed between the paleo-Bear River and the southern subbasin of Gem Valley. Some mixing and flow of paleo-groundwater was especially likely given the fractures and porous basalts along the river's path through the Alexander shield volcano. Thus, the water of the marshes in southern Gem Valley may have been mixed partly with water from the Bear River, even while the clastic sediment there came from the adjacent mountain ranges (Fig. 2.6). Likewise, a lack of a surface water connection of the Bear River into the Bonneville basin in earlier Pleistocene time does not preclude some upper Bear River water making it into the Great Basin through groundwater pathways.

Regarding the mechanism for diversion of the Bear River, although the geochronologic data are currently too sparse to be certain, the ~430-ka eruption and great volume of the two Portneuf basalt flows might reflect the onset of vigorous volcanism and more rapid building of a divide across Gem Valley. Such a scenario was previously proposed by Link et al (1999) to have taken place at 140 ka, based on Armstrong et al.'s (1975) erroneous age of the Portneuf basalt. The building of the mid-basin drainage divide in Gem Valley likely occurred in concert with the somewhat more rapid accumulation of marshy and lacustrine deposits of the upper Main Canyon Formation. The ancestral Bear River's path may have been influenced by lavas flowing downhill from the Tenmile Pass area or along structural depressions within the East Gem Valley fault zone (Janecke and Oaks, 2014). Yet the river's inferred northwestward path across Gem Valley toward the Snake River need not have been diverted toward the southern subbasin until near the end of deposition of the Main Canyon Formation.

2.6.2 Implications of Bear River Drainage Integration

Current chronostratigraphic constraints provide a 60–50-ka timeframe for full southward integration of the Bear River into the Bonneville basin. This interval falls just after, or perhaps overlaps the end of, the penultimate Cutler Dam (MIS 4) lake cycle and well before the most recent Bonneville (MIS 2) lake cycle. Based on lithofacies interpretation, ostracod zonation, and the age model of GLAD800 sediment cores, Balch et al. (2005, fig. 6) interpreted a freshening and rise in lake water of Lake Bonneville between ~40 and 20 ka, stronger than in previous pluvial cycles. Similarly, Nishizawa et al. (2013) presented evidence for unexpectedly high lakestands in the Bonneville basin during MIS 3, between 50 and 25 ka, though these interpretations are disputed (Oviatt et al., 2014). Globally as well as in the southwestern United States (eg, Wagner et al., 2010; Benson et al., 2011; Moseley et al., 2016), MIS 3 (57–24 ka) is recorded as a period of highly variable climate at the millennial timescale. It is possible that the strong climate fluctuations at the onset

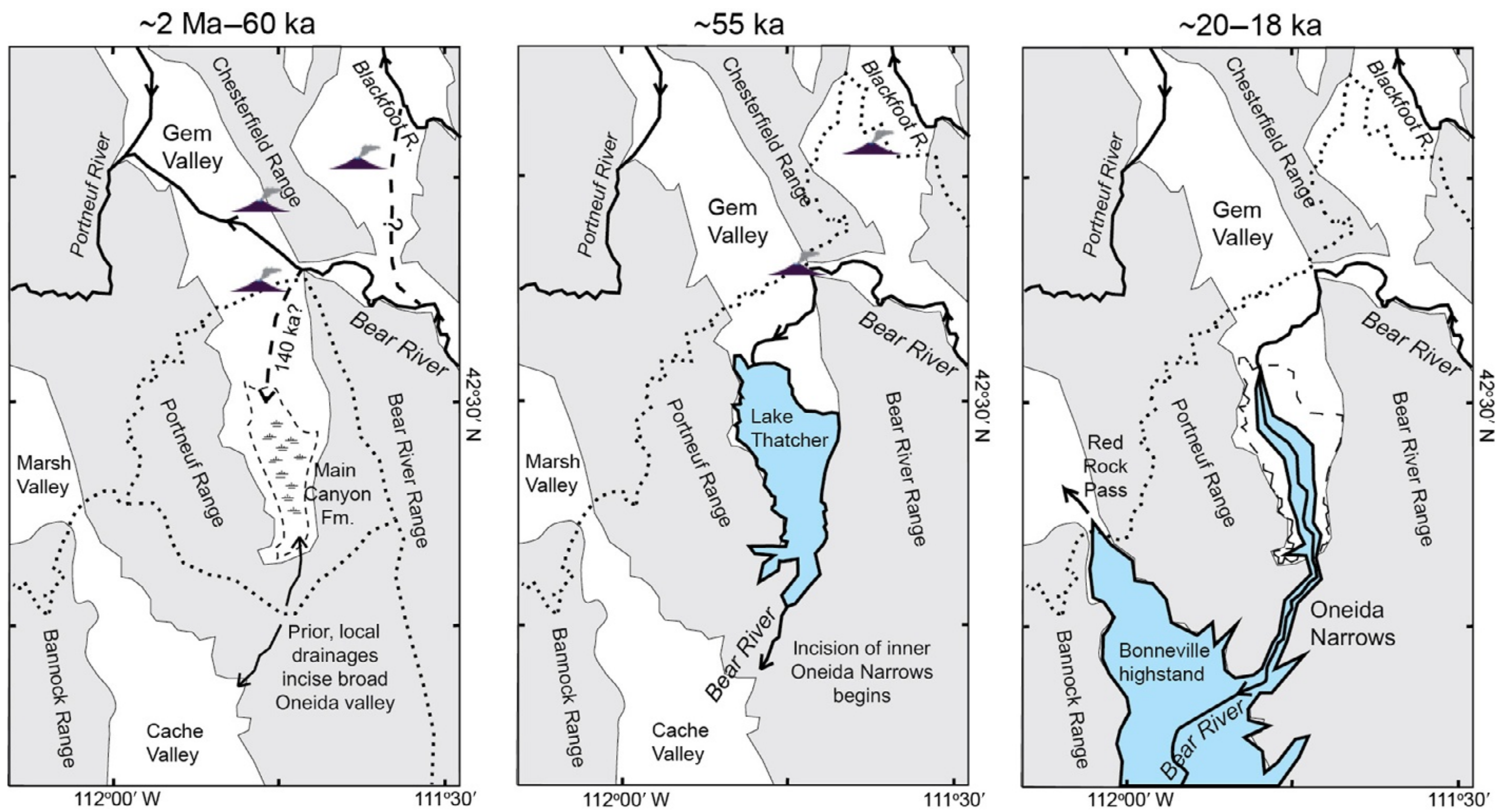

FIG. 2.6 Summary of Quaternary drainage evolution of Gem Valley and Oneida Narrows region in three phases (*dashed lines* represent changing drainage divide). In earlier Plio-Pleistocene time, the upper Bear River possibly could have joined the Blackfoot River, but evidence suggests it connected to the Portneuf River by the late Pleistocene, while internal-basin deposition dominated deposition of the Main Canyon Formation in southern Gem Valley. In the middle panel, eruption of the Alexander shield volcano diverted the river toward the south, raising Lake Thatcher at ~55 ka and causing spillover at the divide in Oneida Narrows, which integrated the river into the Bonneville basin. At right, subsequent incision of the inner gorge of Oneida Narrows and southern Gem Valley allowed Lake Bonneville to backflood far up the Bear River, while its hydrologic addition contributed to spilling of the lake at Red Rock Pass, culminating in the Bonneville flood.

of MIS 3 contributed a hydrologic push for the diversion and integration of the Bear River through southern Gem Valley. Yet, this discussion pertains to a singular, ~55 ka diversion of the Bear River, and not to the potential earlier episode of Bear River water incursion implied by Sr-isotope data from the more distal Bonneville basin, as well as in southern Gem Valley (Bouchard et al., 1998).

The southern Gem Valley record, and the addition of the Bear River's significant discharge to the Bonneville basin, have implications for the pace of Lake Bonneville's rise and its large extent. Although in some cases depicted as an incremental, stepwise progression that took ~10–15 ky (eg, Gilbert, 1890; Oviatt et al., 1992), the rise of Lake Bonneville was very rapid at times (Oviatt, 2015). The backflooding of Oneida Narrows and southern Gem Valley is striking evidence of this. The transgression fully defeated the largest river in the Great Basin and trapped deltaic sediment above the canyon. This is especially impressive considering the significant sediment load of the Bear River, as evidenced by the expansive size of the sandy delta formed later during the Bonneville cycle, both through Oneida Narrows and especially below that canyon in northeastern Cache Valley (eg, Lemons et al., 1996; Anderson and Link, 1998; Janecke and Oaks, 2011).

2.6.3 Primary Unsolved Problems

At the end of this review, it is clear that key gaps remain in our knowledge of the Bear River's history and diversion. For the river's earlier history, it remains unknown whether the Bear River once flowed north to join the present Blackfoot River drainage, and if so, when it was diverted westward toward its likely conjunction with the Portneuf River in Pleistocene time, before it ultimately connected with the Bonneville basin. More dating of key basalt flows and a search for gravel clasts and reddish sediment typical of the upper Bear River along the two proposed river courses could help illuminate this problem.

Of the linked components in the subsequent story of river diversion and integration, one of the least understood is the age and complex stratigraphy of the basaltic volcanism forming the drainage divide across central Gem Valley. These eruptions clearly span the time of Thatcher Basin filling and also after incision of southern Gem Valley due to drainage integration, but it is unknown which one of these eruptions, and of what age, finally did divert the Bear River southward from Soda Point.

A primary unresolved debate with respect to the Bear River's connection to Lake Bonneville is whether the upper river may have entered the Bonneville system prior to its final integration and cutting of the narrows at 60–50 ka. In Gem Valley, evidence in the upper Main Canyon Formation indicates a limited, earlier episode of Bear River water and sediment entering southern Gem Valley ~140 ka. If such an incursion involved the main channel of the

Bear River and lasted more than ~15 years into the restricted subbasin, it would have caused spillover, basin filling, drainage integration, and incision that would seem irreversible, precluding the subsequent and final spillover and integration at ~55 ka. Alternatively, the river could have been diverted from a northwest course into the southern Gem Valley for only a brief time during MIS 6. If so, it is possible that milder, earlier spillovers may have occurred and assisted in partial erosion of Oneida Narrows downstream of the most recent paleo-divide (Fig. 2.5). Indeed, the conclusion that incision of the resistant bedrock of Oneida Narrows was very rapid, stemming from the idea of a singular and later integration event, may itself be a subject for further inquiry. Still, no stratigraphic or sedimentologic evidence for an earlier lake transgression and spillover has been recognized yet in the Gem Valley record. In the greater Bonneville basin, Hart et al.'s (2004) analysis of Sr data suggests the Bear River had an earlier entrance into the basin at or before the Little Valley lake cycle of MIS 6. Yet, somehow the full integration of the river occurred at 60–50 ka according to the Gem Valley record. The resolution of these issues will require further work in southern Gem Valley and Oneida Narrows, especially on the sedimentology and chronostratigraphy of the Main Canyon Formation.

Finally, a related issue that deserves further exploration is whether the important data on Sr-isotope ratios are sensitive to other, unexplored changes of tributary and groundwater pathways. This may include changes related to the also-large Provo River and Weber River drainages, changing contributions from the hot and cold springs common along the Bear River's path, and even of groundwater pathways for some upper Bear River water into southern Gem Valley and perhaps the Bonneville basin earlier in Pleistocene time.

Although there is a long lineage of scientific thought and research recognizing the importance of the changing Bear River in the paleohydrology of the Lake Bonneville record, these and other key questions remain for future work to address. The timing of the final integration of the Bear River into the Great Basin is coming into focus at ~55 ka. Whether this was a singular entrance, or a more drawn-out arrival, the implications for the Bonneville paleoclimate record remain as profound as G.K. Gilbert and Robert Bright first recognized.

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