The Geological Society of America
Special Paper 447
2009

Late Neogene basin history at Honey Lake, northeastern California: Implications for regional tectonics at 3 to 4 Ma

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ABSTRACT

Neogene sediments in a structural and geomorphic high in the southwestern Honey Lake basin represent lacustrine deposition from 3.7 to 2.9 Ma, interrupted once by a significant lowstand. Tephras in the upper section are 3.26 Ma and 3.06 Ma. A thick debris-flow bed, truncated by an erosional surface and overlain concordantly by a thin interval of subaerial sediments, is evidence for lake-level fall at ca. 3.4 Ma. The dominant structure is a broad east-southeast–plunging anticline cut by several sets of faults. These include northwest-striking dextral and northeast-striking sinistral strike-slip faults and a conjugate set of west-northwest–striking thrust faults; all are consistent with north-south shortening. Mutually crosscutting relationships between faults, and tilt fanning of the dextral faults, indicate that tightening of the anticline was synchronous with faulting. A Quaternary strand of the dextral Honey Lake fault crops out near the northern end of the exposure, suggesting that the cause of the local shortening and uplift was a contractional stepover between two strands of the Honey Lake fault. The Neogene section limits this faulting to some time after 2.9 Ma. The Honey Lake basin lies at the intersection of the Walker Lane with the Sierran frontal fault system. Although the timing of tectonic disruption was roughly consistent with passage of the triple junction to the west and with uplift and exhumation of several nearby basins, the described deformation seems to be directly related to dextral faulting, dating the propagation of a strand of the Honey Lake fault through the southwestern Honey Lake basin.

Keywords: Neogene, Walker Lane, strike-slip tectonics, eastern Sierra Nevada.

INTRODUCTION

The Sierra Nevada–Basin and Range transition zone exhibits two different styles of intraplate deformation, east-west extension, and northwest-directed dextral slip. East-west extension, primarily middle Miocene in age, characterizes the central Basin and Range Province and has propagated westward with time into the adjacent Sierra Nevada (e.g., Dilles and Gans, 1995; Surpless et al., 2002). In contrast, extension did not start until 10–12 Ma in the northern Basin and Range (e.g., Colgan and Dumitru, 2003;

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Trexler, J.H., Jr., Park, H.M., Cashman, P.H., and Mass, K.B., 2009, Late Neogene basin history at Honey Lake, northeastern California: Implications for regional tectonics at 3 to 4 Ma, *in* Oldow, J.S., and Cashman, P.H., eds., Late Cenozoic Structure and Evolution of the Great Basin–Sierra Nevada Transition: Geological Society of America Special Paper 447, p. 83–100, doi: 10.1130/2009.2447(06). For permission to copy, contact editing@geosociety.org.

Lerch et al., 2004; Whitehill et al., 2004), suggesting that extension also may be propagating, or stepping, northward with time. The Sierran frontal fault system forms the prominent western topographic boundary of the Basin and Range Province, but it is not the structural boundary: young extensional faulting is occurring within the eastern part of the Sierra "block" (e.g., Hawkins et al., 1986; Mass, 2005; Mass et al., this volume). Strike-slip faulting in the Walker Lane, along the western edge of the Basin and Range Province, has occurred at several times since the initiation of the transform plate boundary (e.g., Hardyman and Oldow, 1991; Oldow, 1992; Cashman and Fontaine, 2000). The most recent dextral slip episode has been attributed to the opening of the Gulf of California and the development of the Eastern California shear zone, starting ca. 6 Ma (e.g., Oskin and Stock, 2003; Faulds et al., 2003). The northwest-trending strike-slip fault system of the Walker Lane intersects the north-trending Sierran frontal fault system just south of Honey Lake, California (Fig. 1).

Neogene sedimentary basins are present in all of these domains: the relatively coherent Sierra Nevada block, the Walker Lane, and the extended regions east and west of the Walker Lane. These basins record the time interval during which the structural domains were developing (Muntean, 2001; Park, 2004; Mass, 2005). Sedimentary facies, provenance, and paleocurrent indicators record the evolving paleogeography during deposition. Interbedded volcanic ash and fossils provide age control. Many of the sedimentary basins in the Sierra Nevada–Basin and Range transition zone are now exhumed; tilting, faulting, and folding of these sedimentary rocks record the postdepositional deformation. Comparison of individual basin histories allows us to constrain the evolution of the Sierra Nevada–Basin and Range transition zone in space and time.

The Honey Lake basin lies near the intersection of Walker Lane dextral faults and the Sierran frontal fault system, and also marks the change from primarily exhumed Neogene sedimentary basins, to the south, to still-active depositional basins on the east side of the Cascade arc, to the north. The Honey Lake basin forms a prominent gravity low (e.g., Cerón, 1992), and most of it is still an active depositional basin. However, part of the Neogene sedimentary section at Honey Lake is exposed at the southwest edge of a topographic and structural high near the south end of the basin, locally known as The Island (Figs. 2, 3). Most of the exposures occur on a small peninsula at the southern end of The Island called the South Island. We have examined these rocks for information regarding the depositional history, age of exhumation, and style of deformation at this unique area in the Sierra Nevada–Basin and Range transition zone.

In this paper we present new sedimentological and structural data from the Neogene rocks at Honey Lake and use these to interpret part of the tectonic evolution of this part of the Sierra Nevada–Basin and Range transition zone. We start with the stratigraphy, sedimentology, and age of the exposed section, the subject of an M.S. thesis by H. Park (Park, 2004; Park et al., 2004). Then we present the deformational record in the local structural high that exposes the sediments; this structural study was part of an M.S. thesis by K. Mass (Mass et al., 2003; Mass, 2005). We conclude with the implications of our results for the style and timing of intraplate deformation in the region.

BACKGROUND

Tectonic Setting

Several important tectonic events in Miocene–Pliocene time influenced the geologic evolution of the Sierra Nevada–Basin and Range transition zone at the latitude of the northern Sierra. At the plate margin the triple junction migrated northward, accompanied by the cessation of subduction and Cascadian volcanism, and changes in the sublithospheric mantle; it passed the latitude of Reno, Nevada, ca. 4 Ma (Atwater and Stock, 1998). Basin and Range extension propagated westward into the Sierran block, possibly related to side heating from the Basin and Range (e.g., Dilles and Gans, 1995; Surpless et al., 2002). Sierran root delamination sometime between 10 and 4 Ma caused uplift and a change in composition of basaltic volcanism in the central Sierra (e.g., Ducea and Saleeby, 1996). Tilting and incision of Neogene sedimentary rocks as young as 2 or 2.5 Ma are evidence for a significantly more recent uplift event in northwestern Nevada and northeastern California (e.g., Trexler et al., 2000; Muntean, 2001; Park, 2004; Cashman and Trexler, 2004; Mass, 2005; Cashman et al., this volume; Mass et al., this volume). Although dextral shear across the continental margin started with the inception of the transform boundary ca. 30 Ma (Atwater, 1970), the accommodation of the shear changed with the opening of the Gulf of California ca. 6 Ma (Oskin and Stock, 2003) and development of the eastern California shear zone. This latest dextral slip may have propagated northward with time, providing an opportunity to examine the development of a major intracontinental fault zone or transform plate boundary (e.g., Faulds et al., 2003, 2004). There is little direct evidence for the age of onset of dextral faulting in the northern Walker Lane; estimates include between 9 and 4 Ma (Cashman and Fontaine, 2000), 6 Ma (Faulds et al., 2003), and 3 Ma (Henry et al., 2002). At the latitude of the White Mountains in central-eastern California, dextral faulting, like normal faulting, has propagated westward with time (e.g., Stockli et al., 2003). It is not yet possible to determine whether this has been the case at the latitude of the northern Sierra.

Because these tectonic events (and the structures that result from them) overlap in space and in time, it can be difficult to determine the precise age, extent, or regional significance of any one event. Our approach has been to study Neogene sedimentary basins in different structural domains, thus isolating specific structural styles and tectonic driving forces. For example, the Honey Lake basin, specifically the Neogene sedimentary section exposed at the South Island, lies within the Walker Lane zone of dextral faults. The postdepositional deformation of these rocks therefore may represent the initiation of dextral faulting in this area, and the age of the youngest deformed sediments constrain its timing. In addition, the Neogene sedimentary record prior to

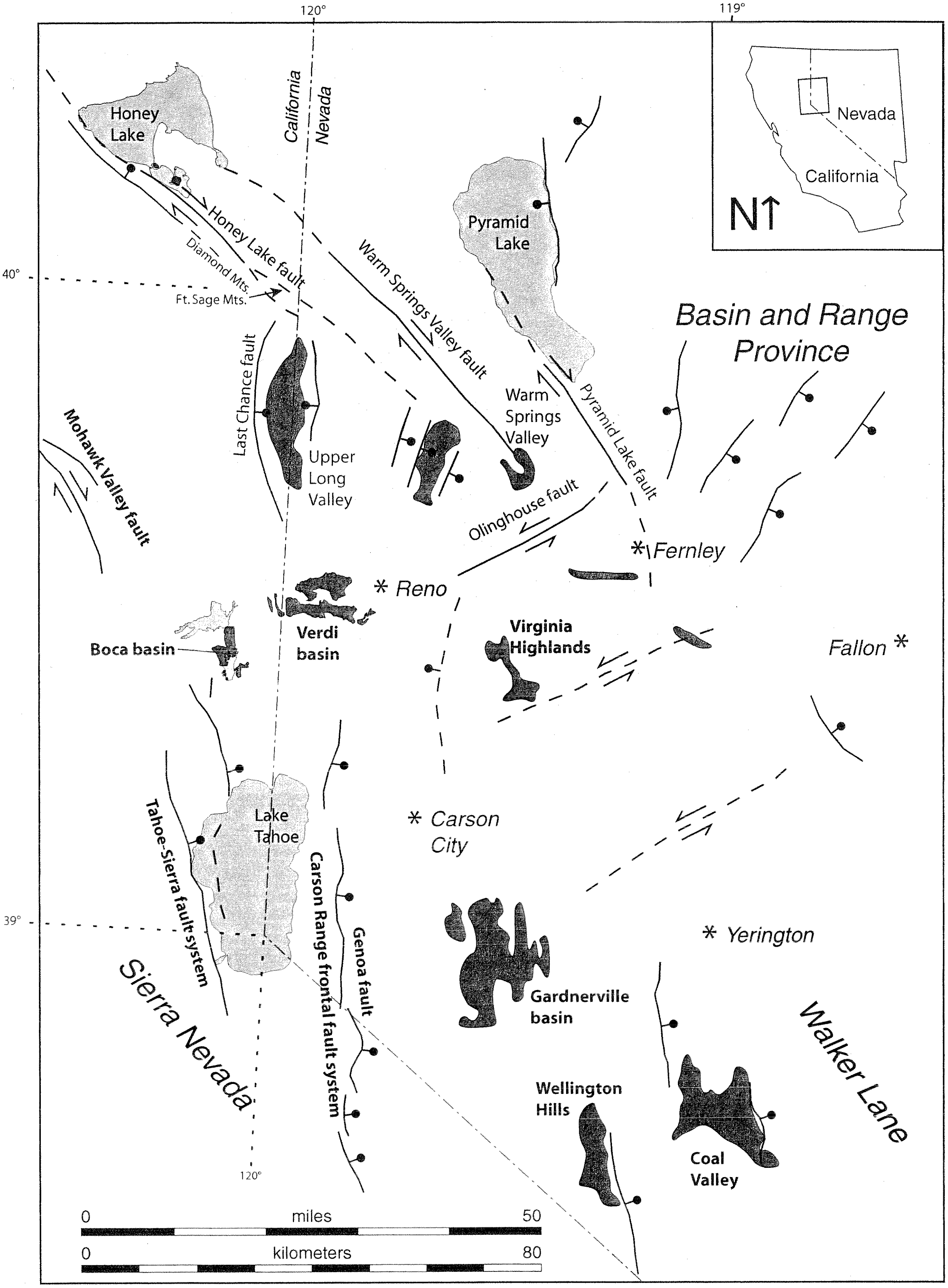


Figure 1. Map of the northern Sierra Nevada–Basin and Range transition zone, showing Neogene basins and major faults. Light-gray shading—Walker Lane. Modified from Mass (2005).

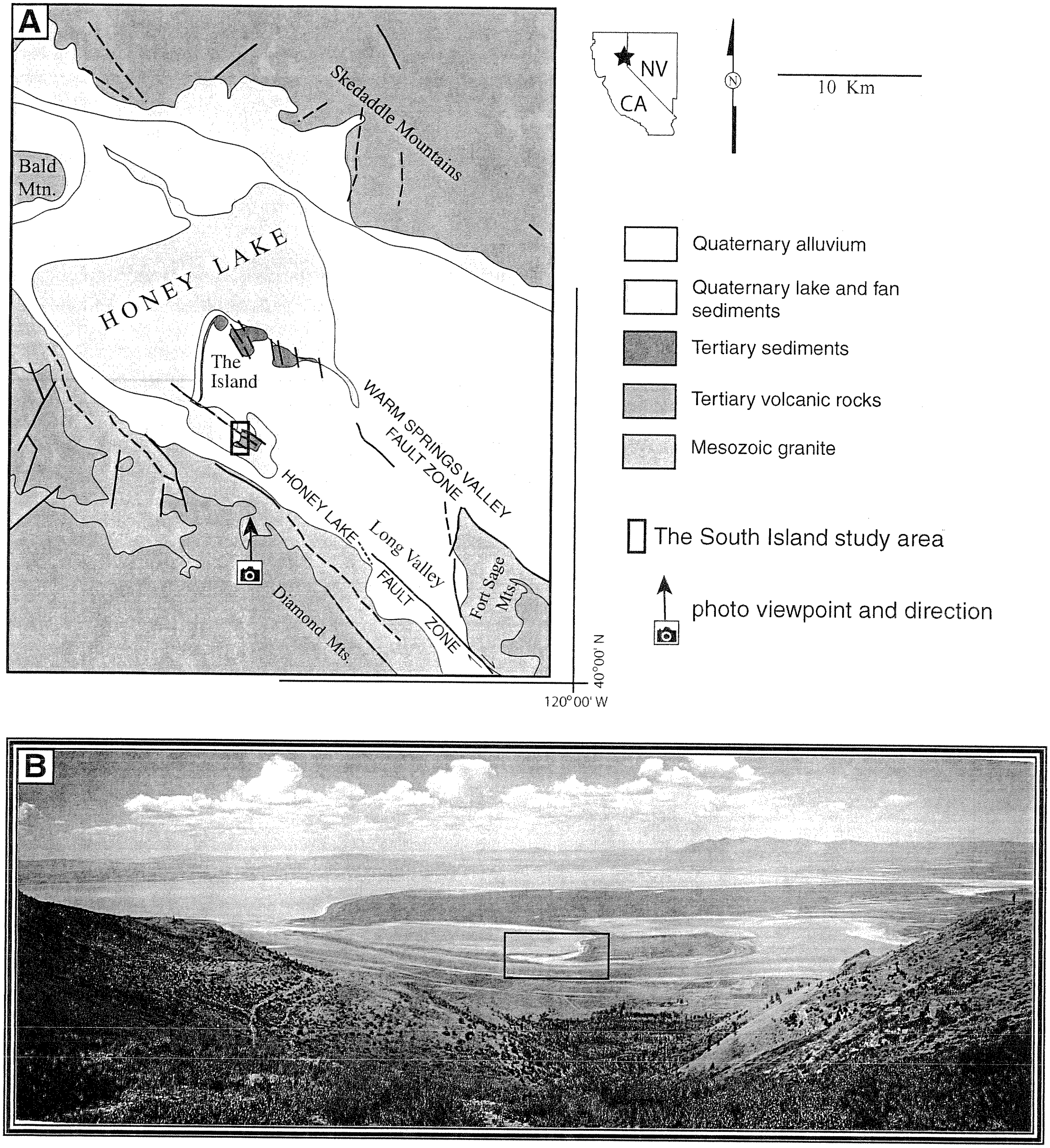


Figure 2. (A) Regional geologic map, showing the geologic and geographic setting of The Island, and the location of the study area on the South Island (geology after Lydon et al., 1960). (B) Photograph taken from the crest of the Diamond Mountains, looking north across Honey Lake. The South Island field area is in the middle distance. Photo credit: Nick Hinz.

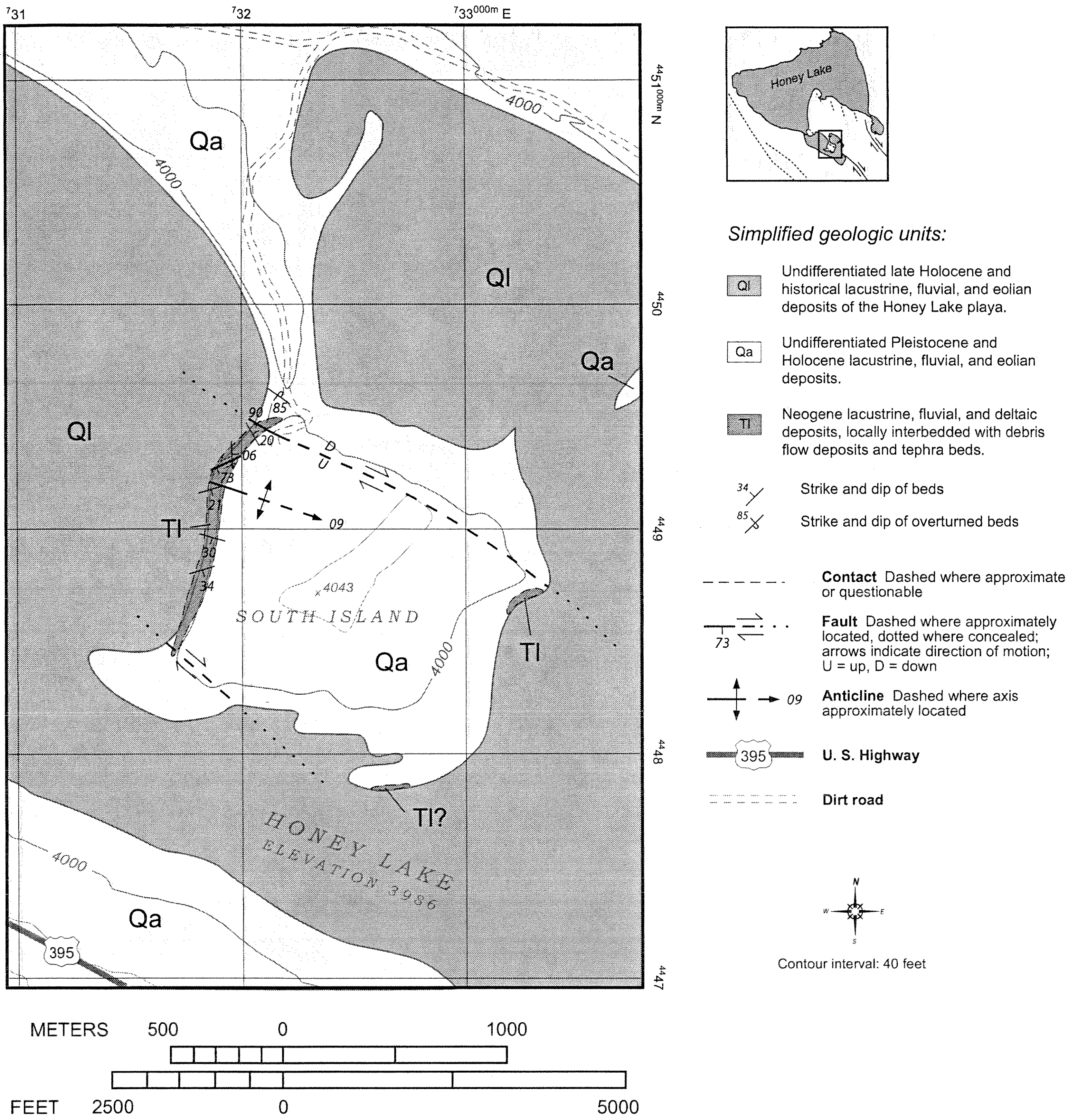


Figure 3. Geologic map of the South Island study area. Note that although regional mapping (Fig. 2) shows Tertiary sediments covering the South Island, in fact most of the sediment at the surface there is Pleistocene or Holocene. Tertiary sediments are well exposed only along wave-cut cliff exposures along the west side of the South Island. Poorly exposed and patchy outcrops are present at the southeast corner of the South Island and the northeast edge of The Island that were not included in this study.

deformation may reveal changes in regional paleogeography that reflect other nearby tectonic events.

Regional Geology

The Honey Lake basin lies within the "Pyramid Lake domain" of the Walker Lane; this northernmost structural domain of the Walker Lane is characterized by northwest-trending, left-stepping dextral faults (Stewart, 1988). In the original definition of the domain the major dextral faults were, from southeast to northwest, the Pyramid Lake, Warm Springs Valley, and Honey Lake faults (Fig. 1). The Mohawk Valley fault, farther west and within the Sierra Nevada, is now commonly included in the domain (e.g., Faulds et al., 2003; Hinz, 2005; Hinz et al., this volume). The Honey Lake fault is mapped along the western edge of the Honey Lake basin. A Quaternary scarp of the Honey Lake fault cuts the eastern edge of the exposed Neogene section we studied at the South Island (Grose et al., 1984; Wills and Borchard, 1993) but cannot be traced in the topography northwestward into the modern lake or playa. A second dextral fault of the Pyramid Lake domain, the Warm Springs Valley fault, projects into the eastern part of the Honey Lake basin from the southeast, along the northeastern boundaries of the Fort Sage Mountains and the South Island (e.g., Grose et al., 1989; Wills and Borchard, 1993). Warm Springs Valley, along fault strike to the southeast, contains Neogene sediments that range from ca. 10 Ma (TenBrink et al., 2000) to 3 Ma (Henry et al., 2003), but little is known about the depositional system(s) or the deformation history of these rocks. The Warm Springs Valley fault has deformed the youngest known part of the Neogene section and latest Pleistocene strata at the northwest end of Warm Springs Valley (e.g., Henry et al., 2004) and has a Holocene scarp in the central part of the valley (Bell, 1984). It is not clear whether the fault continues northwestward under the Quaternary alluvium and lake deposits in the eastern Honey Lake Valley, but the shape of The Island, Honey Lake, and the steep-sided gravity low at the Honey Lake basin (e.g., Cerón, 1992) support this interpretation.

Recent research using paleochannels in the Oligocene tuff section as piercing points has led to better estimates of dextral slip in the Pyramid Lake domain, although the time period over which these dextral faults have acted is not well constrained. Correlation of paleovalley segments between the Diamond and Fort Sage Mountains implies 9.5–17 km of dextral displacement across the Honey Lake fault zone; other constraints favor ~10 km of displacement (Hinz, 2005; Hinz et al., this volume). Interestingly, although the topography suggests significant east-side-down offset across the mountain front along the southwest edge of Honey Lake, the paleovalleys are at virtually the same elevation in the Diamond and Fort Sage Mountains (Hinz, 2005; Hinz et al., this volume), implying little or no dip-slip motion across the Honey Lake fault or a range-front fault during this time. For the Warm Springs Valley fault, the preliminary estimate of dextral displacement based on offset of paleovalleys is 8–10 km (Delwiche et al., 2002; Henry et al., 2004).

The intersection of the normal Sierran frontal fault system with the dextral faults of the Walker Lane is at the northern end of Upper Long Valley, directly southwest of the Honey Lake basin (Fig. 1). Upper Long Valley contains an exhumed, west-tilted Neogene section, with a normal fault—the Upper Long Valley fault—forming its western boundary (Koehler, 1989; Grose and Mergner, 1992); this basin is the northernmost of the exhumed Neogene basins. The Neogene deposits, known as the Hallelujah Formation (e.g., Koehler, 1989; Grose and Mergner, 1992), include ca. 8 Ma rocks low in the exposed section (C.D. Henry, 2000, personal commun.). However, preliminary gravity studies suggest a thick Neogene section along the *east* side of the basin that underlies this dated locality, indicating that basin initiation was well before 8 Ma (TenBrink et al., 2002). Sedimentation included both lacustrine deposition and periods of axial drainage that probably flowed north into the Honey Lake basin (Koehler, 1989; Park, 2004). Coarse, monolithologic debris-flow conglomerates occur throughout the Hallelujah Formation (Koehler, 1989; Grose and Mergner, 1992); these conglomerates have a local source and appear to record syndepositional faulting at several times during the history of the Long Valley basin. The upper age limit for Neogene deposition in Long Valley—and therefore the timing of exhumation—is poorly constrained. Age control comes from Late Blancan (<5 Ma) fossils high in the section (Koehler, 1989), but we do not know how much younger than 5 Ma the youngest of these rocks are.

The dextral faults may be working in combination with normal faults to accommodate dextral slip in the northern Walker Lane (Faulds et al., 2003). Slip on the Pyramid Lake fault appears to transfer northward onto several west-dipping range-front normal faults, and slip on the Warm Springs Valley, Honey Lake, and Mohawk Valley faults may transfer southward onto a series of east-dipping normal faults north of Reno, Nevada (Faulds et al., 2003). One of these normal faults is the Upper Long Valley fault.

STRATIGRAPHY AT HONEY LAKE

Neogene sediments of the Honey Lake basin are exposed in scattered outcrops around the north end of Honey Lake, although mapping there has not been published (Roberts, 1985), and in an excellent and continuous exposure of a broad anticline at a low topographic rise on the South Island at the southwest end of the lake (Fig. 3). More than 600 m of section at the South Island was studied and described in detail by Park (2004), whose thesis is the basis for the following sedimentary descriptions. Other than these limited outcrops, little is exposed of the Neogene Honey Lake basin stratigraphy, although strata are presumed to be extensive underneath the modern playa.

Investigations at the north end of Honey Lake (Roberts, 1985) document two sedimentary sections, at Bald Mountain and Rice's Canyon, that are Miocene and Pliocene in age; these establish an older limit for the Neogene section. The lower section is intercalated with 10 Ma andesitic volcanic rocks, and the upper part preserves Miocene–Pliocene flora. The upper section includes diatomite and tephra, and is capped by 4.9 Ma basalt. These sections are older than the exposed sections at the South Island. There is no reported sedimentary section in the northern part of the basin younger than 4.9 Ma and older than Pleistocene. We did not include these older Tertiary sediments in our investigation. Small and disconnected patches of presumed Tertiary sedimentary rocks are also exposed on the northern shore of The Island, and reconnaissance investigation suggests that these rocks are part of the younger Honey Lake section. These limited exposures were not included in this study.

Two long and detailed stratigraphic sections were measured at the South Island, one on each limb of the anticline. The north limb yields 185 m of section, and the south limb, 435 m. Although faults cut the center of the anticline, the two limbs can be correlated (Fig. 4). The result is two overlapping sections from slightly different positions in the lake's paleogeography.

Lithologic Description

Neogene sediments are silt- to sand-sized grains of quartz, feldspar, mica, and lithics, with minor amounts of clay and diatoms. Virtually all clasts larger than coarse sand are unlithified rip-up clasts derived from previously deposited Neogene lacustrine sediments. Some of these are quite large, up to several meters in size. No large clasts of granite or volcanic rock were observed in the section.

Two sediment sources are implied by the clastic material in the South Island section. The provenance of coarse clasts (pebble size and larger), consisting of unlithified rip-ups of subjacent Neogene sediments, is entirely within the basin. In contrast, coarse sand and finer material is consistent with a granitic or felsic volcanic source. The north-sloping fan (see discussion of paleoslope, below) was geometrically aligned with the axis of the Neogene Honey Lake basin. The Neogene Upper Long Valley basin, preserved in an uplifted valley southwest of Honey Lake, also shares this axial alignment and trend (Fig. 1). Mesozoic granitic rocks and Oligocene tuffs are widespread south of the Honey Lake basin, so sediment composition does not identify a unique provenance for these rocks.

Diatomaceous sediments are common in the South Island section, especially in finer-grained intervals. However, clean diatomite was not deposited in this section. The finer parts of the section are dominated by hemipelagic silt. Diatoms identified by Park (2004) are consistent with deep-water lacustrine conditions. The most common assemblage is *Aulacoseira* (or *Meloseira*), *Stephanodiscus carconensis*, *Stephanodiscus niagarae, Stephanodiscus elgeri, Cyclotella stylorum,* and *Cyclostephanos*, which are tychoplanktonic and euplanktonic diatoms (Fig. 5). In the diatom study of Nakayamadiara palaeolake, Japan (Yamaoka and Shimada, 1962), a depth of 150 m is suggested from the diatom assemblage for *Aulacoseira, Stephanodiscus, and Cyclotella*, which is the same diatom assemblage found in the Honey Lake Neogene sediments.

Thin tephras occur throughout the section; 65 were sampled, of which 10 were analyzed. Of these, two were identified by Mike Perkins (2004, personal commun.) and are used for age control in this study.

Description and Interpretation of Sedimentology

Sedimentary structures commonly include graded beds with scoured bed bases and diffuse tops. Lamination is uncommon, and cross-lamination is rare. The coarse clasts of the graded beds are rip-up clasts, and most were unlithified at the time of deposition. All sedimentary structures in these sections are consistent with a depositional-environment interpretation of a turbidite-dominated, sublacustrine fan.

The sedimentary section is interpreted to have been dominated by density-modified flow deposits, primarily turbidites and debris-flow sediments. Density-modified flow deposits with a grain-size range and a mud/sand ratio of this type are described by Gani (2004). Most of these sandy turbidites are unchannelized, but in a few localities eroded channels are filled with turbidites. In some intervals, bed-thickness trends indicate coarsening and thickening, lobe-building relationships (Fig. 6). The fine-grained intervals in between turbidites are hemipelagic silt and mud. These hemipelagic parts of the section commonly have a significant diatomite component. Detailed sedimentology and facies analysis are documented by Park (2004).

The north limb section contains a single, thick, and very coarse debris-flow deposit low in the section. Blocks in the debris flow are up to 10 m in long dimension, and all are rip-up clasts of the underlying lacustrine sediment. Most clasts and blocks are deformed, and some are folded (Fig. 7). At the base of the debris bed are partially detached turbidite beds that are rolled into the flow. The sense of shear in the debris flow is tops-north, as it is in all paleoslope indicators here (discussed below).

Soft-sediment deformation is common throughout the Honey Lake section. Structures that record soft-sediment failure include load casts, flame structures, detached and distorted bedding, and ball-and-pillow structures. A continuum of deformed beds can be defined, from simple loading to debris slides and flows. Most deformed or broken bedding shows soft-fold vergence and rip-up imbrication, which is evidence of downslope movement toward the north (Fig. 8).

In both north and south limb sections an important unconformity breaks the stratigraphy. In the north limb section this unconformity caps the thick debris flow. In the south limb section it caps a thick, channelized sand unit that is correlated with the debris flow and presumed to be a mass-flow channel-filling sand. A distinctive, pyroclastic (lapilli)–dominated bed just above the unconformity in both sections confirms the correlation. In both sections the unconformity is scoured and is overlain by cross-laminated, coarse, micaceous sandstone that leveled out micro-paleotopography. We interpret this unconformity as a lacustrine lowstand that formed an erosional surface capped by a thin, fluvial conglomerate and sandstone interval

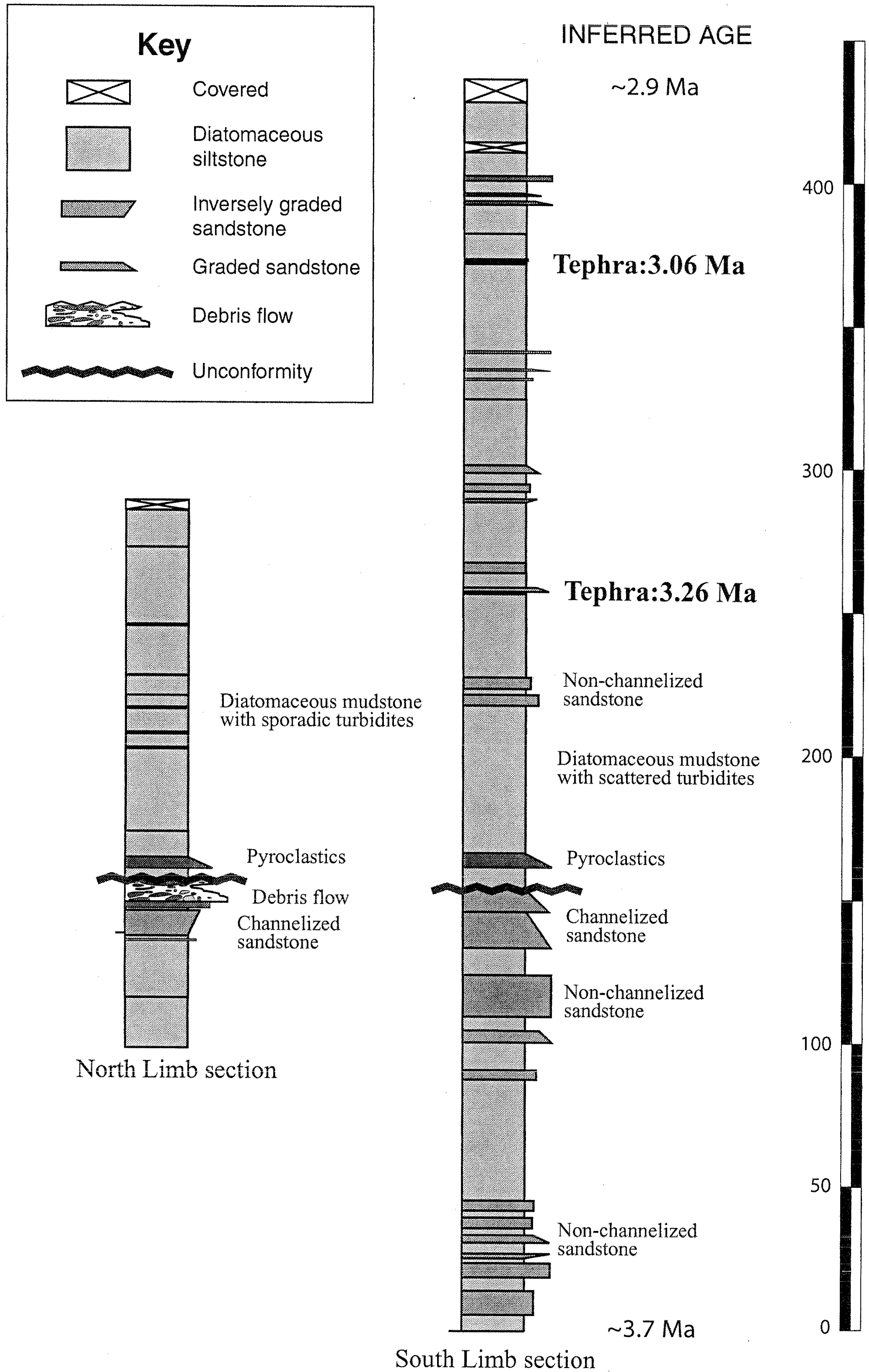


Figure 4. Composite stratigraphic column for Neogene sediments at The Island, from Park (2004). The sections from the north and south limbs of the anticline are correlated on the basis of the erosional surface, underlying channelized sandstone, and distinctive overlying pyroclastic (lapilli-dominated) zones. The time scale is based on the deposition rate calculated from the two dated tephras in the south limb section. Vertical scale at right in meters.

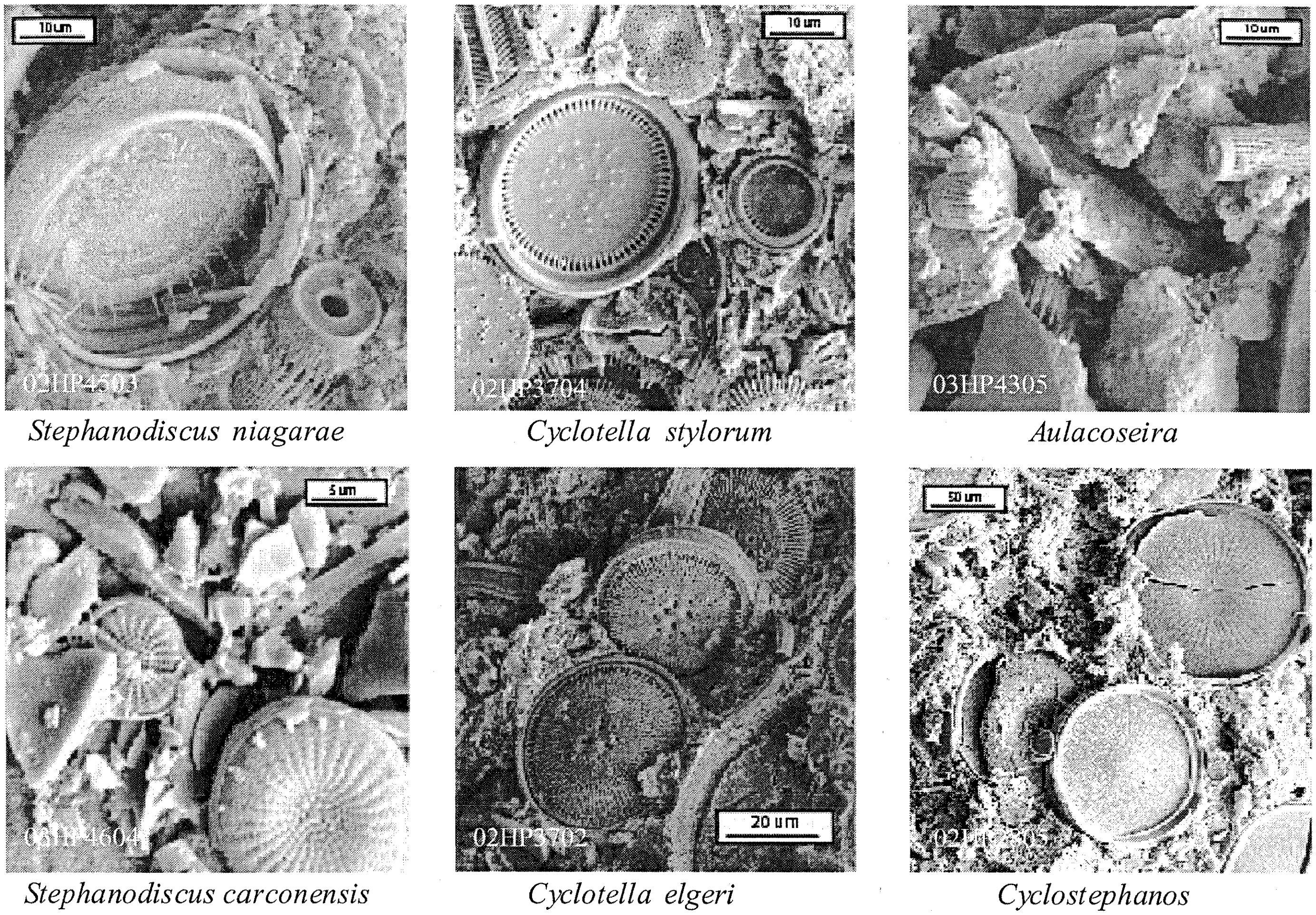


Figure 5. Diatoms common in the Honey Lake diatomaceous siltstone. Photomicrographs from Park (2004).

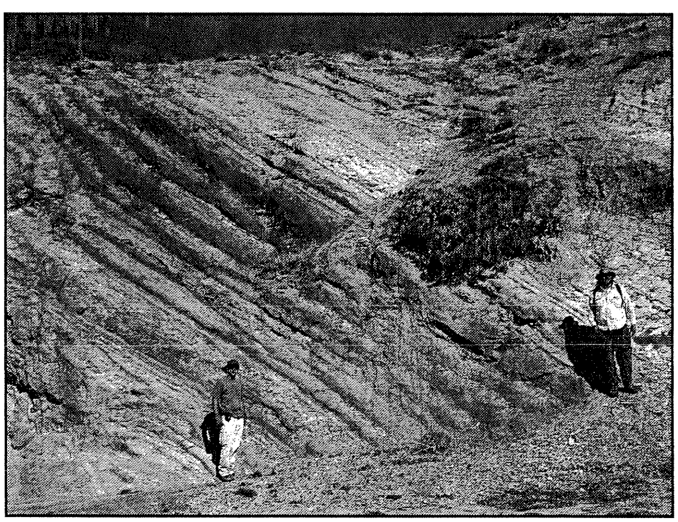


Figure 6. A coarsening-thickening-upward succession of turbidites, interpreted as a sublacustrine fan-lobe sequence.

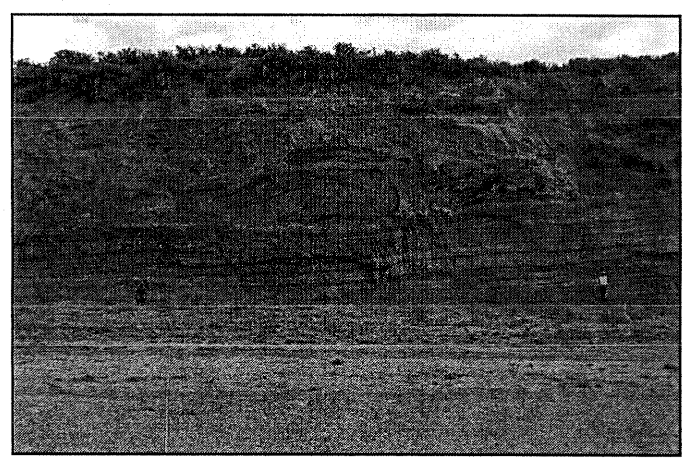


Figure 7. View, looking east, of the thick debris-flow deposit directly below the 3.45 Ma unconformity in the north limb section. Blocks in the debris flow are rip-up clasts of the underlying lacustrine sediment; folding of clasts indicates downslope-to-the-north displacement. The debris flow may be related to instability during a lacustrine lowstand, or to tectonic activity possibly as a coseismic event. Note students for scale.

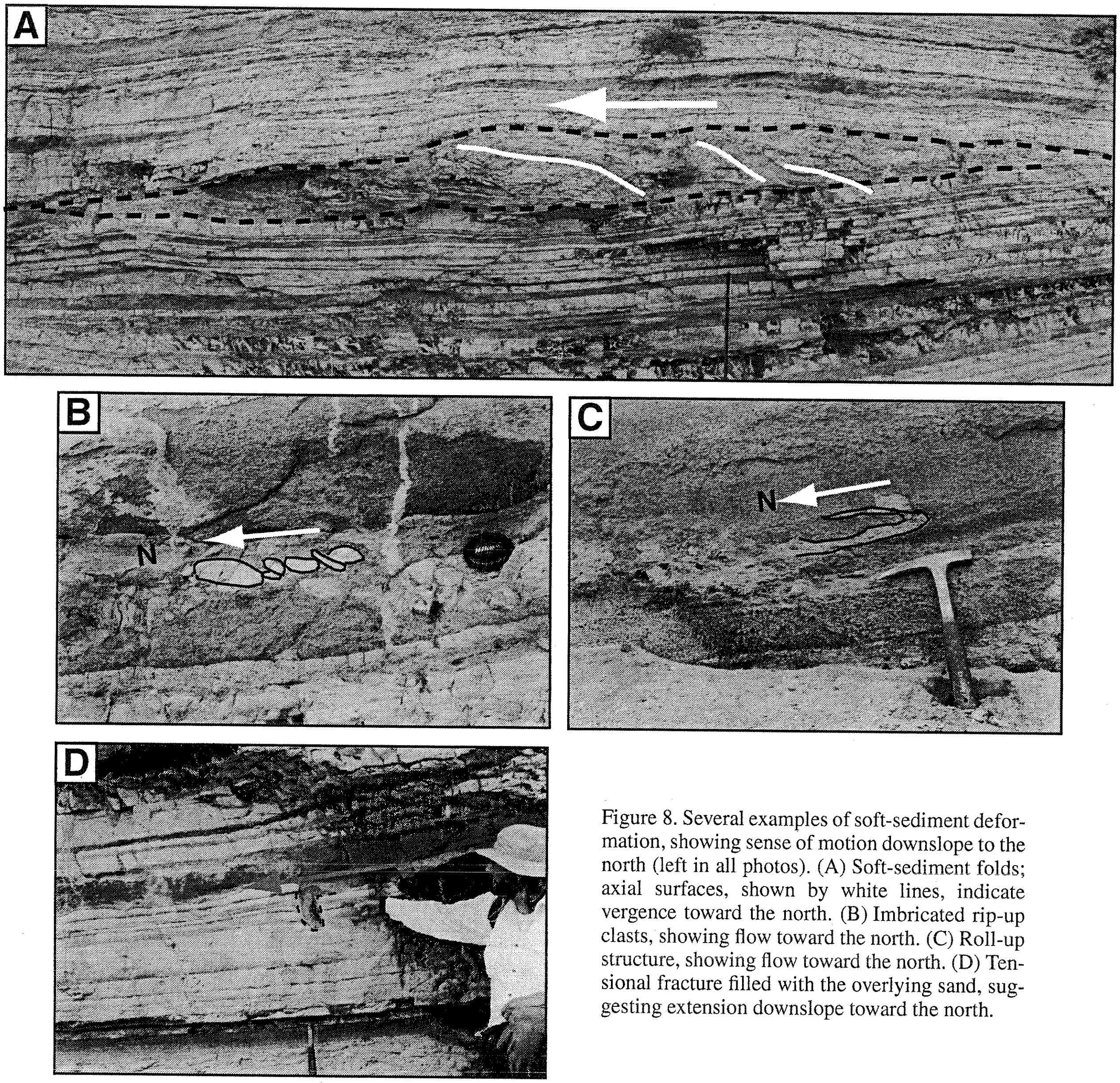


Figure 8. Several examples of soft-sediment deformation, showing sense of motion downslope to the north (left in all photos). (A) Soft-sediment folds; axial surfaces, shown by white lines, indicate vergence toward the north. (B) Imbricated rip-up clasts, showing flow toward the north. (C) Roll-up structure, showing flow toward the north. (D) Tensional fracture filled with the overlying sand, suggesting extension downslope toward the north.

that is unique in the sections. The overlying turbidites record a return to lacustrine conditions.

Age Control

Two tephras ~100 m apart in the Honey Lake section have been identified and correlated with regional ash beds: one at 3.26 Ma, and another at 3.06 Ma (Fig. 4; Perkins, 2004, written commun.). By interpolation, these tephras allow an estimation of lake sedimentation rate at 550 m per million years. This rate, in turn, allows estimation of the age range of the exposed south-limb section of ca. 3.7 Ma to 2.9 Ma.

Summary: Depositional Environment of the South Island Section

The Neogene section at the South Island represents ~800,000 yr of lacustrine deposition, interrupted once by a significant lowstand. These sediments were deposited on a north-sloping axial ramp at the south end of the Honey Lake basin, with a significant sediment source to the south. There are no paleoslope indicators or any coarse clastic debris that would be evidence of a source-area uplift to the west (modern Diamond Mountains) or east (modern Skedaddle Mountains). Sedimentation was dominated by sandy turbidites and hemipelagic mud, with some silty diatomaceous intervals. The dominance of fine clastic sediments and the lack of clean diatomite intervals are consistent with deposition as a prodelta slope rather than a part of the basin isolated from active sedimentation. Diatoms identified by Park (2004) are consistent with deepwater (>150 m) lacustrine conditions.

The Neogene sediments were very unstable, as recorded by the abundant evidence of sediment failure and collapse. Everywhere in the South Island section the paleoslope was steep enough so that once mobilized, sediments sheared downslope to the north. The sediment instability and failure here can be attributed to three possible explanations (e.g., see discussion by Leeder, 1999):

1. A high sedimentation rate contributed to autocyclic failure. This phenomenon occurs as rapid sedimentation overpressures a saturated sediment column, resulting in fluid escape. Common evidence in known examples includes sand volcanoes and dewatering structures extending upward through the section to the coeval sediment-water interface.
2. A dramatic lake-level drop destabilized sediments, causing dewatering and allocyclic failure. As water level and hydrostatic pressure fell, interstitial water pressure became greater, and subsequent fluid escape caused sediment deformation and failure.
3. Co-seismic shaking caused intergranular instability and loss of material strength, resulting in allocyclic failure. Such failure can also result from shock caused by storm waves in open-marine environments, but this cause can be discounted for lakes the size of the Honey Lake basin.

Any of these mechanisms is possible in the South Island section.

The dramatic combination of the thick debris-flow bed, the erosional surface that truncates it, and the thin overlying interval of subaerial sediments is evidence for a rapid lake-level fall at ca. 3.4 Ma. Rothwell et al. (1998) invoke low sea level as a possible trigger for large submarine landslides (for the Pleistocene case they document, buried organic matter and methane hydrate also played a role). The debris flow may have been triggered by subaerial exposure of the upper (southern) part of the delta as lake level dropped, resulting in erosion and resedimentation of inner-delta sediments down the delta slope. Alternatively, seismic shaking may have triggered the debris flow, although there is no direct evidence for this. In any case, although subaerial exposure followed the debris-flow event, the lake soon returned, and lacustrine sedimentation continued much as before. There is no evidence of angular discordance across the lowstand boundary, so local tectonism is not required as a cause for the lake-level drop. Lake-level response to climate change also is a viable possibility.

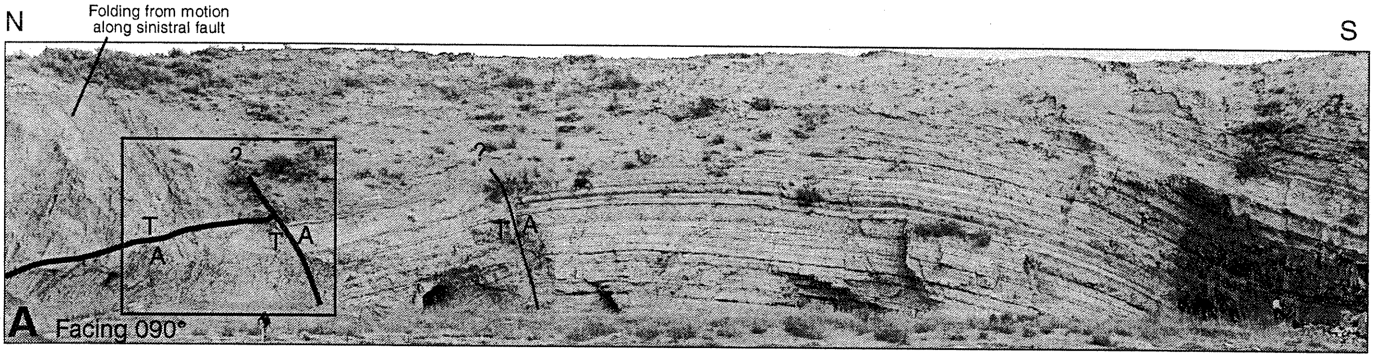
POST-DEPOSITIONAL DEFORMATION RECORDED AT HONEY LAKE

The Neogene section exposed at the South Island is in a structural high formed by a broad east-southeast–plunging anticline (Figs. 3 and 9). This anticline is cut by two strike-slip faults that have tens of meters of offset, and by numerous mesoscopic faults. A northwest-striking dextral fault near the north end of the exposure displaces the ground surface and alluvial gravels as well as the Neogene section (Fig. 10), and has been mapped as an active strand of the Honey Lake fault zone (Grose et al., 1984; Wills and Borchard, 1993). Bedding is locally vertical in the vicinity of this fault; this amount of deformation suggests significant displacement on the fault. A northeast-striking sinistral fault near the core of the anticline is also associated with strong localized drag folding, and bedding cannot be matched across the fault; both suggest relatively large offset (tens of meters or greater?). Mesoscopic faults are common throughout the anticline, but fault offsets are small enough (most are of centimeter to meter scale) so that the stratigraphy can be reconstructed across the faults. Kinematic indicators are present on ~40% of the small faults; sense of slip on the remainder is inferred from the combination of stratigraphic separation and analogy with similarly oriented faults of known slip sense. The faults can be divided into three main sets, in order of abundance: northwest- to north-northwest–striking dextral faults, east-northeast- to east-southeast–striking sinistral faults, and thrust faults that are most commonly west-northwest striking. The following structural descriptions are summarized from Mass (2005).

The most abundant faults in the exposed Neogene section are subvertical northwest- to north-northwest–striking dextral faults. Slickenlines and grooves on these fault surfaces plunge <10° to the northwest or southeast, recording pure strike-slip motion (Fig. 11). Riedel shears and stratigraphic separation indicate dextral slip. The dextral faults appear to have been active throughout the deformation history of the Neogene section, and this deformation continues with the Quaternary fault that offsets the ground surface at the north end of the outcrop on the South Island. There appears to be some tilt-fanning of the dextral faults across the core of the anticline, suggesting that some of these faults were present prior to formation of the anticline and that tightening of the anticline has been synchronous with dextral faulting. This dextral fault set, not including the Quaternary fault that offsets the ground surface, accommodates at least 10 m of cumulative displacement.

The northeast- to east-striking sinistral faults are more variable in both strike and dip than the dextral faults (Fig. 12). The few kinematic indicators (other than stratigraphic separation) that are preserved are subhorizontal on northeast-striking surfaces. Slip indicators are slightly steeper on east-striking surfaces and indicate oblique sinistral-reverse slip. The sinistral faults have mutually crosscutting relationships with the thrust faults, and both seem to have formed to accommodate space problems during tightening of the anticline (see below) (Figs. 9 and 10). This sinistral fault set, not including the major sinistral fault near the core of the anticline, accommodates at least 5 m of cumulative displacement.

Mesoscopic west-northwest–striking faults constitute a conjugate set that dips gently northeast or southwest, and stratigraphic separations consistently show that the hanging wall moved up



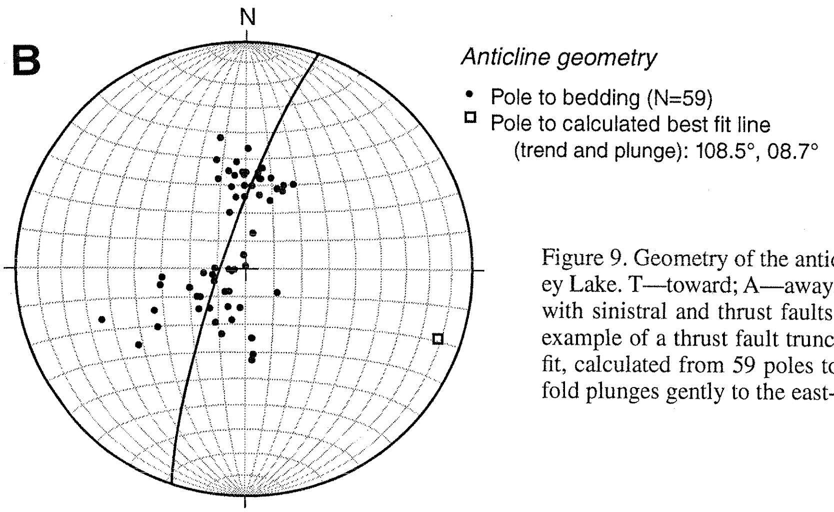


Figure 9. Geometry of the anticline exposed along the west shore of The Island at Honey Lake. T—toward; A—away. (A) Mosaic of photos, showing the core of the anticline with sinistral and thrust faults (students for scale). The area inside the box shows an example of a thrust fault truncated by a sinistral strike-slip fault. (B) Great circle best fit, calculated from 59 poles to bedding across the ~1 km exposure, indicates that the fold plunges gently to the east-southeast.

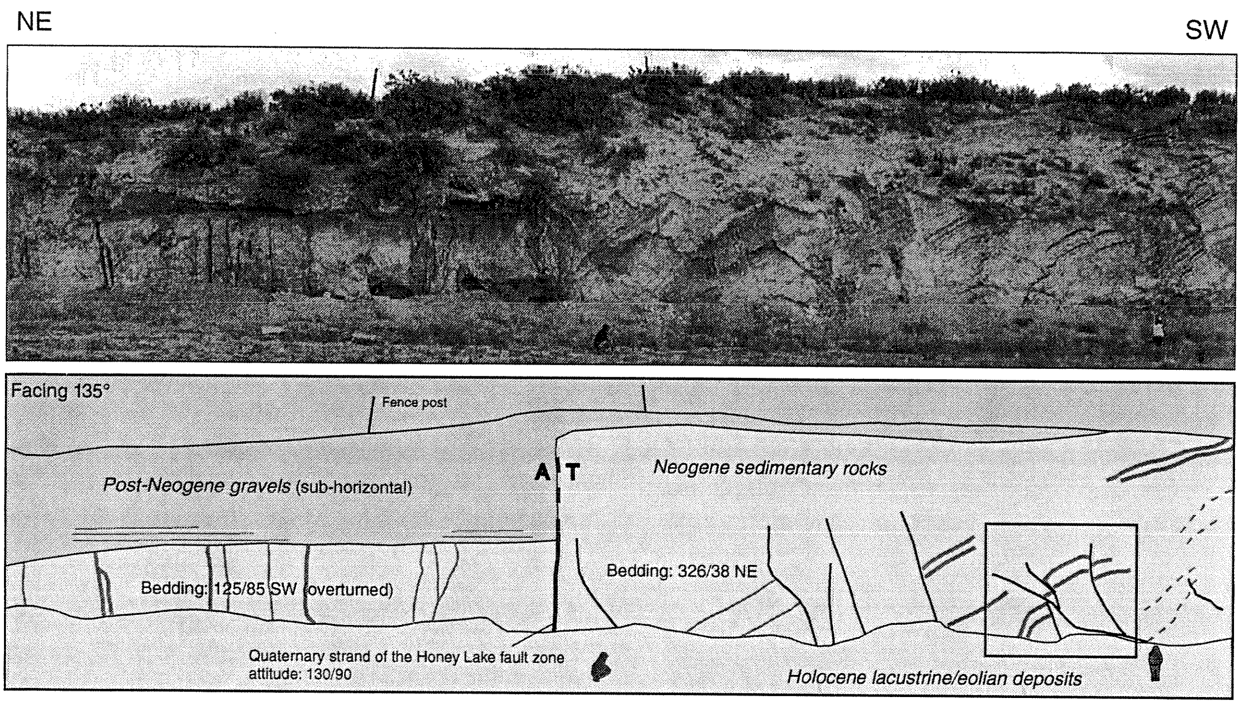


Figure 10. A Quaternary strand of the Honey Lake fault zone is exposed at the northern termination of the anticline. Sandstone beds (gray) in silty diatomite (light gray) change dip dramatically across the fault. Minor faults include dextral and sinistral strike-slip faults and thrust faults, and show crosscutting relationships locally. The area inside the box shows an example of a sinistral strike-slip fault cut by a thrust fault. Note students for scale. T—toward; A—away.

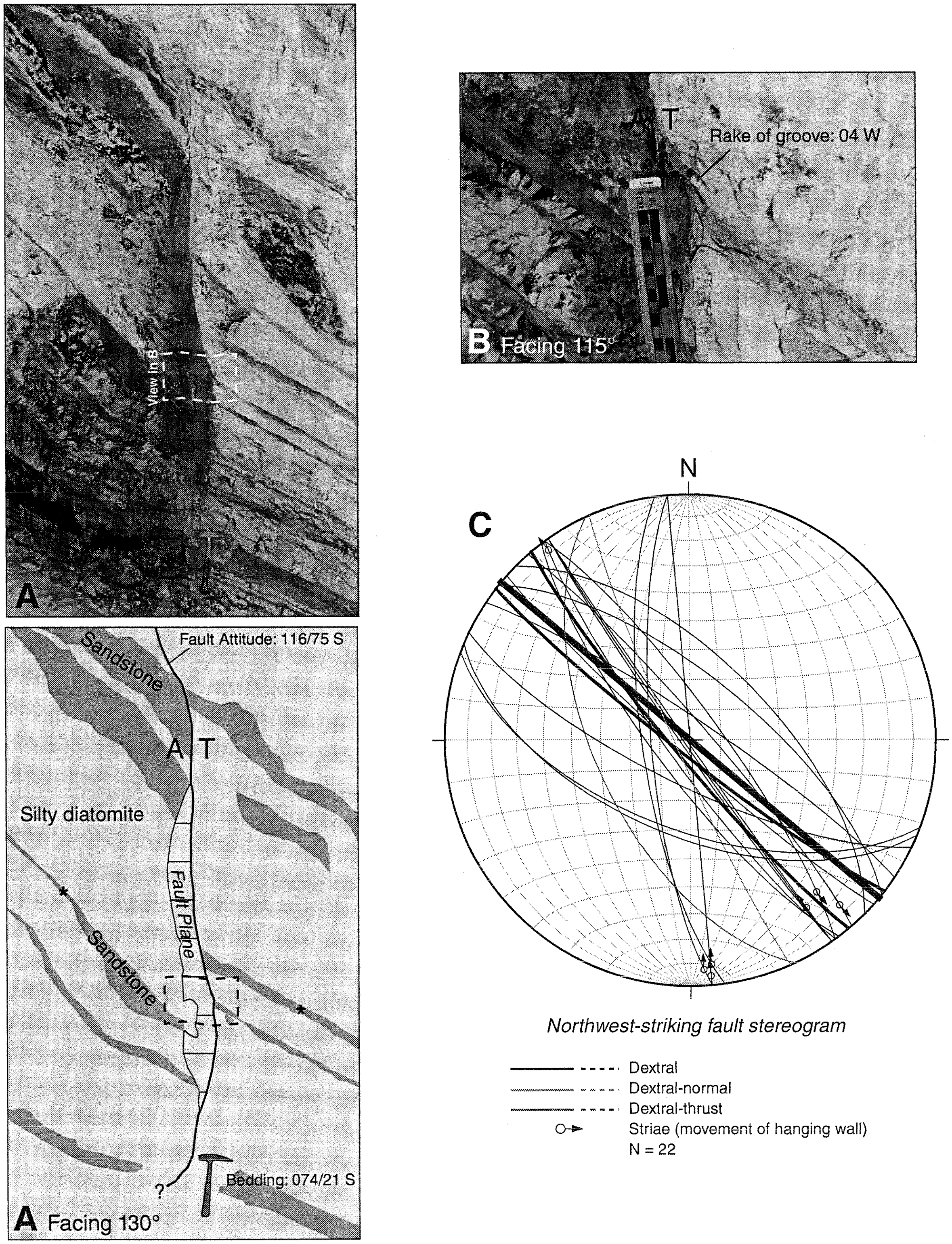


Figure 11. A northwest-striking dextral fault displaces sandstone layers on the south limb of the anticline. T—toward; A—away. (A) The thin gray sandstone at center (*) has a total vertical stratigraphic separation of ~0.2 m. (B) Subhorizontal grooves on the fault plane indicate strike-slip motion. This particular fault has ~2.3 m of total displacement. (C) Equal-area, lower hemisphere stereographic projection of northwest-striking faults interpreted to have dextral motion (22 planes). Thicker lines indicate faults with greater displacement. Although striae are not preserved on most fault surfaces, where they are present they are consistently subhorizontal.

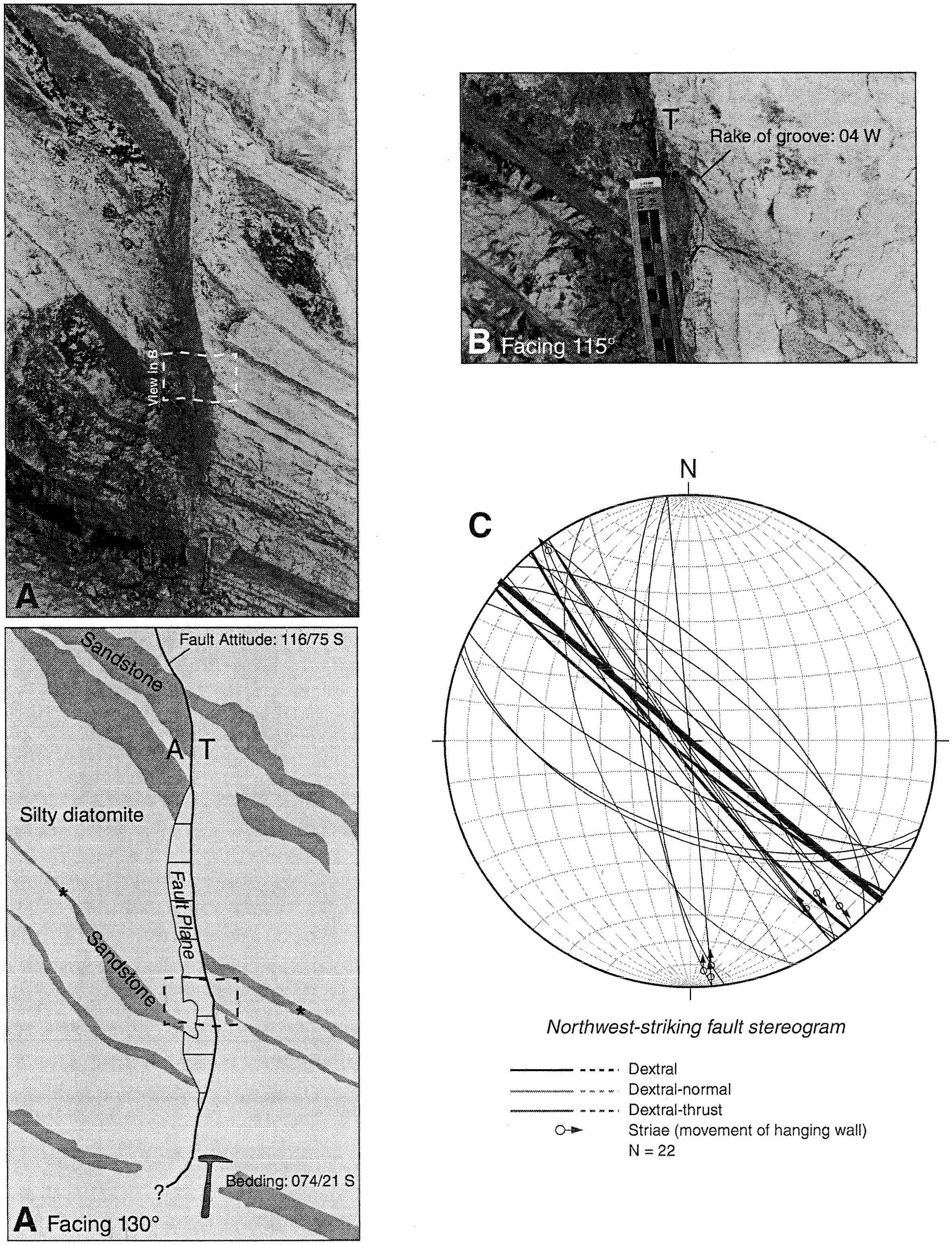
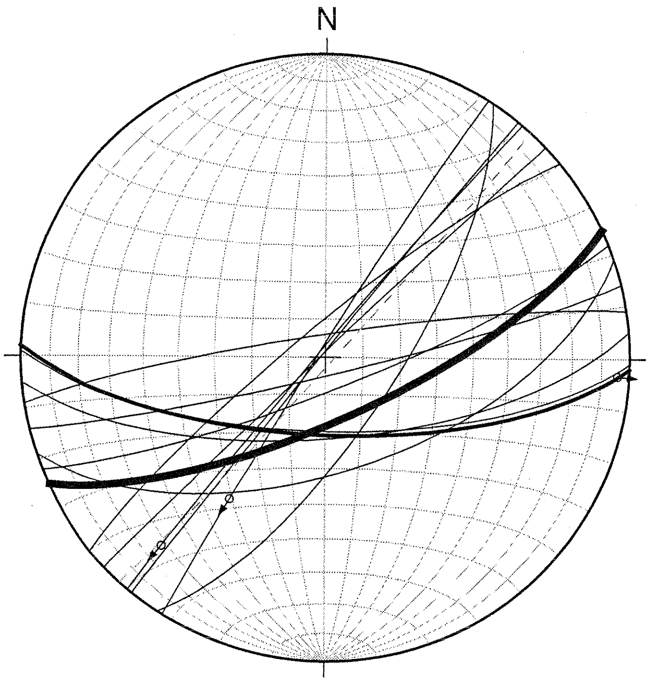


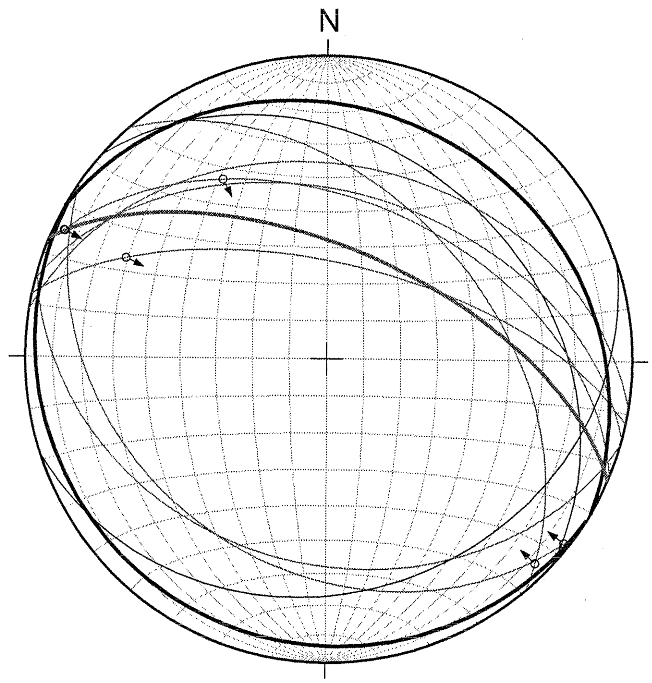
Figure 11. A northwest-striking dextral fault displaces sandstone layers on the south limb of the anticline. T—toward; A—away. (A) The thin gray sandstone at center (*) has a total vertical stratigraphic separation of ~0.2 m. (B) Subhorizontal grooves on the fault plane indicate strike-slip motion. This particular fault has ~2.3 m of total displacement. (C) Equal-area, lower hemisphere stereographic projection of northwest-striking faults interpreted to have dextral motion (22 planes). Thicker lines indicate faults with greater displacement. Although striae are not preserved on most fault surfaces, where they are present they are consistently subhorizontal.



Northeast-striking fault stereogram

—— ---- Sinistral
O→ Striae (movement of hanging wall)
N = 15

Figure 12. Equal-area, lower hemisphere stereographic projection of northeast-striking faults interpreted to have sinistral motion (15 planes). Thicker lines indicate faults with greater displacement. Striae are not preserved on most of these faults, but drag folding and offset bedding indicate sinistral motion.



West-striking fault stereogram

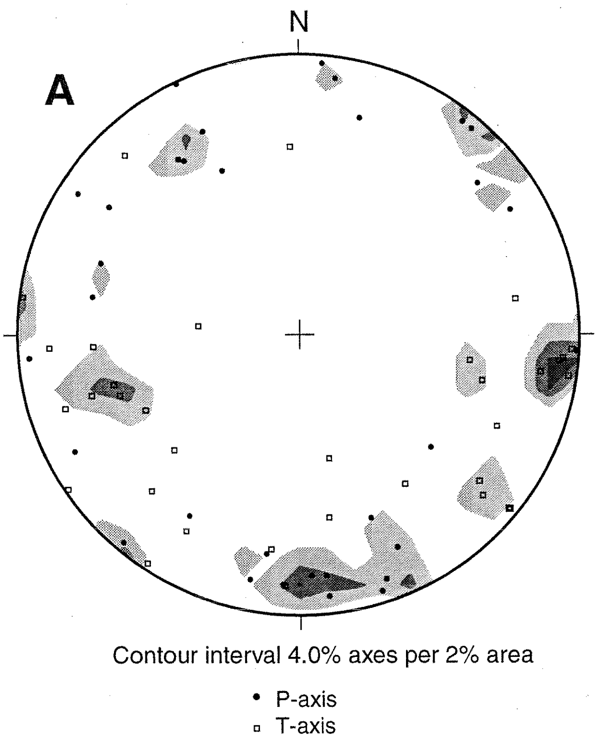
—— ----- Thrust
—— ----- Sinistral-thrust
O→ Striae (movement of hanging wall)
N = 11

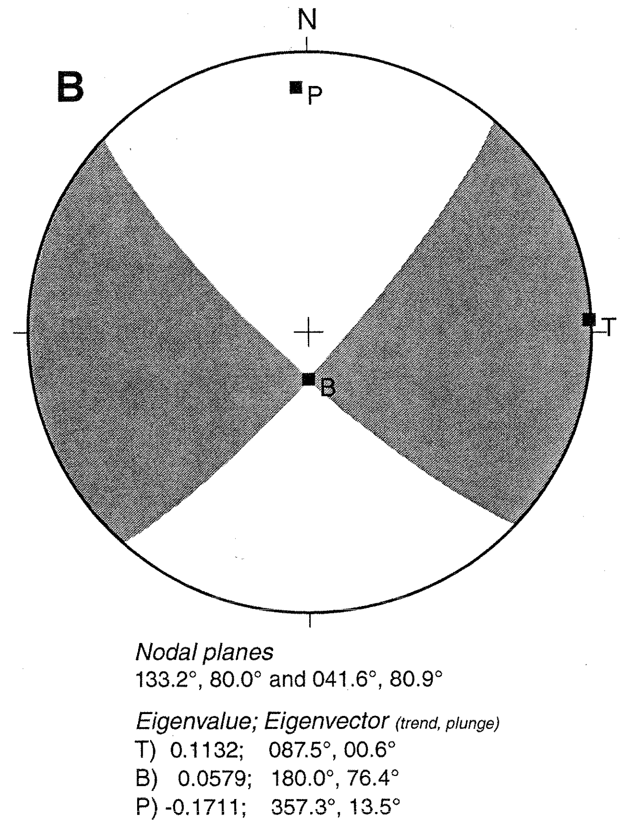
Figure 13. Equal-area, lower hemisphere stereographic projection of west-striking conjugate faults interpreted to have thrust motion (11 planes). Thicker lines indicate faults with greater displacement. Note that most striae are not consistent with thrust motion. These striae are interpreted to indicate reactivation of these fault surfaces during strike-slip events on nearby faults.

relative to the footwall (Figs. 9, 10, and 13). These faults are interpreted to be thrust faults, resulting from north-northeast–south-southwest shortening, which is consistent with the strain recorded by the broad anticline. The thrust faults show mutually crosscutting relationships with sinistral faults, both in the core and on the north limb of the anticline, indicating that the two were active simultaneously (Figs. 9 and 10). Multiple generations of thrusting—oblique thrust and sinistral faults, particularly in the core of the anticline—attest to continuing activity of the faults during folding. The few striae preserved on the thrust faults record northwest-southeast slip at a low angle to the fault strike, which is an unlikely initial slip direction for gently dipping faults. The northwest-trending striae probably represent reactivation of some of the thrust-fault surfaces during northwest-directed dextral slip along the dominant northwest-striking dextral fault set, possibly as coseismic deformation during motion on the nearby Quaternary fault.

Three-dimensional strain can be determined using a fault inversion method, based on individual faults that have kinematic indicators (Marrett and Allmendinger, 1990). The method assumes that regional strain is uniform and invariant over time. The fault data for the analysis must form over a relatively short time interval, and all faults must be included in the data set. The Honey Lake fault data presented here conform to these criteria, with one caveat: Only faults with kinematic indicators can be used, and these make up a relatively small (but on the basis of the consistent slip directions they show, probably a representative) percentage of the faults (Figs. 8, 10–12). Although the maximum and minimum strain directions determined from the analysis may not necessarily correspond to the extensional and contractional axes for individual faults, the inversion method is reasonable for many faults distributed over a large area (Pollard et al., 1993), such as the ~1-km-length cliff exposures on the South Island.

The fault inversion shows that the faults have accommodated approximately east-west extension and north-south contraction, with total extension smaller than contraction; motion on the three main fault sets is consistent with this strain field (Fig. 14A, B). The dextral nodal plane from the fault plane solution strikes 313°, which corresponds well with the measured 310° strike of the





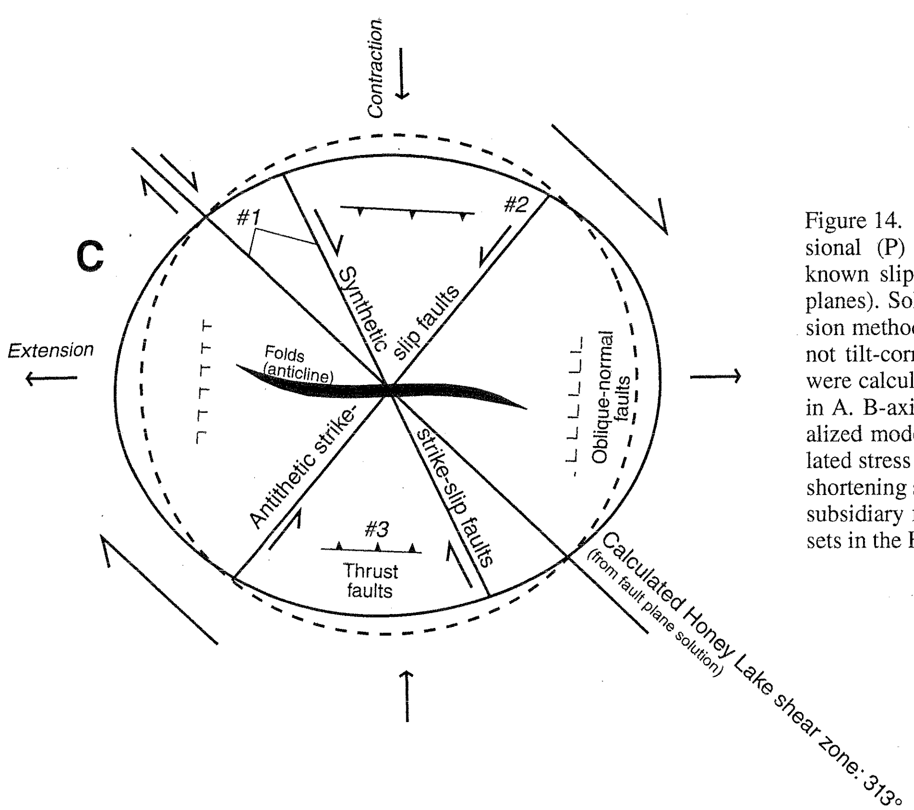


Figure 14. (A) Contoured tensile (T) and compressional (P) stress-axis orientations for faults with known slip direction and displacement >0.1 m (47 planes). Solutions were modeled using a fault-inversion method (program of R. Allmendinger). Data are not tilt-corrected. (B) Nodal planes and stress axes were calculated by combining all of the faults shown in A. B-axis is the intermediate stress axis. (C) Idealized model of structures associated with the calculated stress field (east-west extension and north-south shortening stress is predicted). Note that the predicted subsidiary fault sets are similar to the observed fault sets in the Honey Lake basin.

Quaternary fault strand of the Honey Lake fault zone (Fig. 10). Predicted subsidiary fault sets for this strike-slip shear zone are similar to the observed fault sets of the Neogene Honey Lake basin (cf. Sylvester, 1988) (Fig. 14C). The synthetic dextral faults have a northwest strike (fault set no. 1), while antithetic sinistral faults have a northeast strike (fault set no. 2) and are less abundant than the synthetic faults. The thrust and oblique-thrust faults (fault set no. 3) have a west strike, which is perpendicular to the maximum contraction direction. The trend and plunge of the anticline (109°/09°) is also consistent with the orientation of the maximum contraction direction (Fig. 9). The few sinistral-normal faults on the south limb of the anticline are compatible with the maximum extensional direction.

In summary, the deformation of the Neogene section at the South Island is consistent with north-south shortening and with the regional northwest-striking dextral faults of the Walker Lane. The broad anticline and conjugate set of thrust faults indicate north-south shortening; northwest-striking dextral and northeast-striking sinistral faults are consistent with this strain field. Mutually crosscutting relationships between the thrust and strike-slip fault sets, and possible tilt fanning of the dextral faults, suggest that tightening of the anticline was synchronous with faulting. Faulting at the core of the anticline may in part have accommodated space problems that developed during tightening of the fold. The prevalence of the northwest-striking dextral-fault set, as well as the presence of a Quaternary dextral fault, suggests that these faults are accommodating some of the regional dextral slip of the Walker Lane in addition to local north-south shortening at the South Island. A fault-inversion analysis, using only the faults with kinematic indicators, shows that these faults accommodated subhorizontal north-south shortening and subhorizontal east-west extension (Fig. 14). The nodal planes correspond to many of the measured (northwest-striking dextral and northeast-striking sinistral) strike-slip faults. The northwest-striking nodal plane closely parallels the active strand of the dextral Honey Lake fault at the northeast end of the exposures at the South Island.

DISCUSSION—IMPLICATIONS FOR REGIONAL TECTONICS

The lacustrine Neogene section exposed at the South Island represents only a small, and relatively young, portion of the depositional history of the Honey Lake basin. In exposures northwest of Honey Lake, fluvial lithic wacke and lacustrine diatomite are interbedded with Miocene (10.1 Ma) andesite and Pliocene ash deposits, suggesting that deposition has been active in this basin since at least middle Miocene time (Roberts, 1985). An estimate of depth to basement based on gravity modeling yielded an independent but consistent age of basin initiation ca. 10 Ma (Cerón, 1992). The initiation of sedimentation in the basin does not necessarily represent a tectonic event; the local volcanism could have created the enclosed basin.

The South Island section records the paleogeography at the south end of the Honey Lake basin from ca. 3.7 to 2.9 Ma. The section consists of lake-slope or delta deposits, both pelagic and hemipelagic; diatoms in the finer-grained layers suggest lake depths of ~150 m. The calculated sedimentation rate (550 m per million years) is high for lacustrine deposits but is consistent with this setting, because the hemipelagic sediments and diatoms were supplemented by, and could have been overwhelmed by, the clastic input from the rivers feeding the delta systems. The composition of the clastic material is consistent with derivation from an intermediate to felsic igneous source; lithic clasts are rare in these generally fine-grained sediments, so a more specific provenance description is not possible.

Interpretation of the Honey Lake sediments as deltaic is consistent both geometrically and geographically with possibly coeval fluvial sediments of the Hallelujah Formation of Upper Long Valley (e.g., Koehler, 1989; Grose and Mergner, 1992), an argument supported by both paleocurrent and slope-direction indicators at Honey Lake. The Hallelujah Formation fluvial system may have been the upstream part of a river-delta-fan drainage. Alternatively, the Hallelujah Formation may have been exhumed and eroded, and that debris redeposited in the Honey Lake basin. Because of insufficient age control for the Hallelujah Formation, it is not yet possible to distinguish between these two possibilities, thereby testing the model of kinematic linkage between dextral and normal faults (Faulds et al., 2003) on the basis of the section at the South Island.

A significant lake-lowering event occurred at ca. 3.4 Ma. Age control suggests that the lowstand had a short duration and that lacustrine deposition had resumed after a brief period of subaerial erosion and fluvial deposition. There is no evidence of angular discordance across the lowstand boundary, so local faulting is not required as a cause for the lake-level drop. Because lacustrine sedimentation was quickly reestablished, large-scale topographic rearrangement is not indicated. A climatically driven lowstand cannot be ruled out. However, the coincidence of the thick debris-flow deposits and the drop in lake level are suggestive of tectonic processes.

The anomalous structural high that exposes the Neogene section is interpreted to have formed in a contractional stepover between two strands of the Honey Lake fault. Folding and faulting of the Neogene section are consistent with north-south shortening, and our fault-inversion analysis gives similar results. Mutually crosscutting relationships between the thrust and strike-slip fault sets, and possible tilt fanning of the dextral faults, suggest that tightening of the anticline was synchronous with mesoscopic faulting. An active strand of the dextral Honey Lake fault crops out at the northeast end of the South Island exposures; it offsets the ground surface as well as the sedimentary section. Dextral slip on this surface is consistent with the strain field represented by the postdepositional structures. The coincidence of this fault with the end of Neogene exposures suggests that the cause of the local shortening and uplift is a contractional stepover—i.e., a left step between two strands of the dextral Honey Lake fault. The tephra dates from the South Island section, and the sedimentation rate calculated from them, indicate that the currently active strands of the Honey Lake fault did not propagate through this area until some time after 2.9 Ma.

By analogy with the local structural high that exposes the Neogene section, The Island as a whole appears to be a broad structural high formed by a contractional stepover between the Warm Springs Valley and Honey Lake fault systems. The parallel, northwest-trending boundaries of The Island are along strike with the Honey Lake and Warm Springs Valley faults (Fig. 2). This interpretation also explains both the presence of The Island as a topographic feature and its abrupt termination along trend to the northwest, as shown in gravity data (Cerón, 1992). If correct, this interpretation implies that the Warm Springs Valley fault extends northwest of Warm Springs Valley and the Fort Sage Mountains into the Honey Lake basin.

Like several other Neogene basins along or within the eastern edge of the Sierra, the Honey Lake basin was a lacustrine environment until <3 Ma, but the similarity of timing between basins may be coincidental. Sedimentation (primarily lacustrine) continued in the Verdi basin, directly west of Reno, and the Boca basin, west of Verdi within the Sierra, until <2.6 and ca. 2.7 Ma, respectively (e.g., Mass et al., this volume). The tectonism that terminated deposition in these two basins also exhumed them. In contrast, the tectonism that exposed the section at the South Island was local; most of the Honey Lake basin is still structurally low. The top of the exposed Honey Lake section is slightly <3 Ma; a younger deformed section may exist but is not exposed. Another contrast with the Verdi and Boca basins is that the Honey Lake basin may also record tectonism ca. 3.4 Ma (the lake-lowering event associated with the thick debris flow), and there is no similar evidence at Verdi or Boca.

In summary, the short geologic history recorded in the sedimentary section at the South Island contains evidence of only one of the important Miocene–Pliocene tectonic events in the region. Although the timing of tectonic disruption is roughly consistent with passage of the triple junction to the west and with uplift and exhumation of several nearby basins (the latter possibly related to Sierran root delamination), the deformation at the South Island appears to be directly related to dextral faulting. It therefore appears to date the propagation of a strand of the Honey Lake fault through southwestern Honey Lake. The fact that the rest of the Honey Lake basin remains structurally low is consistent with a contractional-stepover origin for the South Island and suggests that the forces responsible for exhumation of nearby Neogene basins are not active here. The Neogene section at the South Island contains no direct record of regional normal faulting, so it does not place additional constraints on northward or westward propagation of normal faulting, or on kinematic linkage between normal and dextral faulting in the northern Walker Lane.

ACKNOWLEDGMENTS

Dave Wagner at the California Geological Survey originally called our attention to the spectacular exposures at the South Island and has always been available and willing to discuss the regional geology with us. The Biology Department at the University of Nevada, Reno (UNR), provided access to the South Island, which is part of the University of Nevada Research Station at Honey Lake. Carl Lee, station caretaker, was generous with his time and resources. Gary Oppliger discussed gravity data with us and helped us interpret the data. John McCormack helped with photographs of diatoms on the UNR scanning electron microscope. Work with diatoms was partially funded through Alan Wallace and the U.S. Geological Survey. Mike Perkins at the University of Utah helped with collection of tephras and provided identification and age data. The authors also wish to thank Alan Wallace, Becky Dorsey, and John Oldow for very helpful reviews.

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Manuscript Accepted by the Society 21 July 2008

Printed in the USA