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QUATERNARY RESEARCH 11, 21–51 (1979)

Reevaluation of Multiparameter Relative Dating Techniques and Their Application to the Glacial Sequence Along the Eastern Escarpment of the Sierra Nevada, California

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Received January 31, 1978

Four valleys, recently studied by other workers, were examined along the eastern Sierra Nevada to refine relative-dating techniques. A variety of weathering parameters and soil properties fail to delineate more than two major post-Sherwin Pleistocene glaciations. We correlate these two glaciations with the Tahoe and Tioga Glaciations. Type Mono Basin Till, usually considered to be pre-Tahoe, exhibits the following weathering similarities with Tahoe Till, if both are under sagebrush: (1) grusification of subsurface granitic boulders; (2) degree of pitting, mineral relief, and rind development on surface granitic boulders; and (3) very slight clay increase in the B horizon. Type Casa Diablo Till also has weathering characteristics similar to Tahoe Till, except a slightly more developed Bt horizon is present. Hence, dates on basalt of 0.126 ± 0.025 and 0.062 ± 0.013 my Casa Diablo Till also has weathering characteristics similar to Tahoe Till, except a slightly more developed Bt horizaon is present. Hence, dates on basalt of 0.126 ± 0.025 and 0.062 ± 0.013 my (Bailey *et al.* 1976), which bracket type Casa Diablo, may provide age control on the Tahoe Glaciation. In addition, we are unable to demonstrate that the Tenaya is a separate glaciation. In three of the four valleys studied our weathering data for Tenaya Till are equivalent with those for Tioga Till, but with those for Tahoe Till in the fourth valley. We were not satisfied with our ability to differentiate the Casa Diablo, Mono Basin, and Tenaya as separate glaciations even though data were collected in the type areas for two of these deposits. Reasons for suggesting a change back to a two-fold Tahoe–Tioga glacial sequence, rather than the present five-fold sequence, are that we have measured a greater number of parameters than has been done previously, soils were submitted to detailed laboratory analyses, and surface weathering features were studied under consistent present vegetation cover to avoid possible problems induced by ancient forest fires. Nevertheless our relative-dating scheme does not rule out the possibility of a more detailed glacial sequence.

INTRODUCTION

Use of semiquantitative weathering data for age differentiation of glacial deposits along the eastern Sierra Nevada started with the pioneer work of Blackwelder (1931). However, relative dating (RD) techniques now widely used by many Quaternary workers result from the more recent work of Sharp and Birman (1963), Birman (1964), and Sharp (1969, 1972) in the Sierra Nevada, and indeed these works form the basis for the stratigraphic nomenclature and approximate ages presently used for Sierra Nevada glacial deposits. The eastern Sierra Nevada was picked as a major study area in our efforts to advance RD techniques because of extensive previous work (Wahrhaftig and Birman, 1965; Bateman and Wahrhaftig, 1966). The work presented in this paper is part of a larger study to evaluate soil and weathering characteristics as correlation criteria for Quaternary deposits, and to evaluate rates of weathering over parts of the western United States.

RD is based upon the premise that certain weathering parameters are time dependent, and therefore they can be used to delineate episodes of deposition. The need to understand and to use RD techniques arises from the scarcity of radiometric dating control for many surficial Quaternary sequences. In the past, stratigraphic sequences often have been subdivided on a single weathering characteristic. An example is rock

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weathering; however, it may be difficult to effectively use this criterion in other areas where the rock types are different. Hence, we apply several RD techniques in an attempt to determine which parameters provide the best data for till subdivision locally and for correlation over a larger area. This multiparameter approach reduces the possibility of mistakes in subdivision and correlation due to local (nontemporal) variation of a key parameter, and was best summarized by Blackwelder (1931, p. 880):

> Of all these criteria only a few can usually be applied in any one place. One of them alone affords only a tentative opinion, but when several of them all point to the same conclusion confidence is much strengthened.

Our approach was to obtain quantitative data on several weathering and soil phenomena for each major deposit. The number of measurements per deposit, however, has to be sufficiently limited so that the data can be effectively incorporated into a mapping program. As expected, no one phenomenon is universally useful in till differentiation; however, some are more consistent than others and a few apparently do not work in the Sierra Nevada. In contrast to our approach, some workers in the past have made multiple measurements on a deposit of a few parameters, and then used an average value for age assignment. This latter approach has the advantage of producing lots of the same type of data and thus assessing the variability of a parameter within a single moraine. A shortcoming of our approach may be that we do not have data on "within-moraine" variability. However, gathering data on a variety of parameters may be as effective in age determination as increasing the number of measurements on only a few parameters. This will remain to be further tested in the future.

Study sites were selected which had been well studied previously and within which there were minimal differences in nontemporal weathering and soil-forming factors; in this way we sought to increase the probability that variations in RD data reflect different durations of weathering. The four valleys of this study are Sawmill Canyon of the Owens River drainage (designated Sawmill Canyon (S)), Mammoth Creek, the Sawmill Canyon (N)—Bloody Canyon area near Mono Lake, and Green Creek (Fig. 1). A total of 58 man days were spent in collecting the weathering and soils data during July and August of 1975 and 1976.

The data generated in this study suggest a revision of the stratigraphic nomenclature presently used in the Sierra Nevada. In a previous paper (Birkeland *et al.* 1976) we

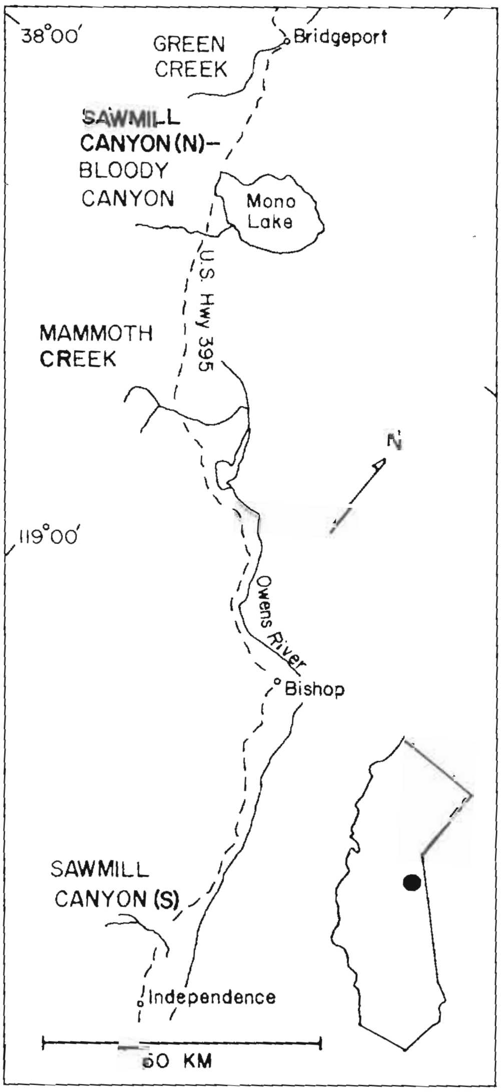

FIG. 1. Regional index map showing major study areas, east-central Sierra Nevada, California.

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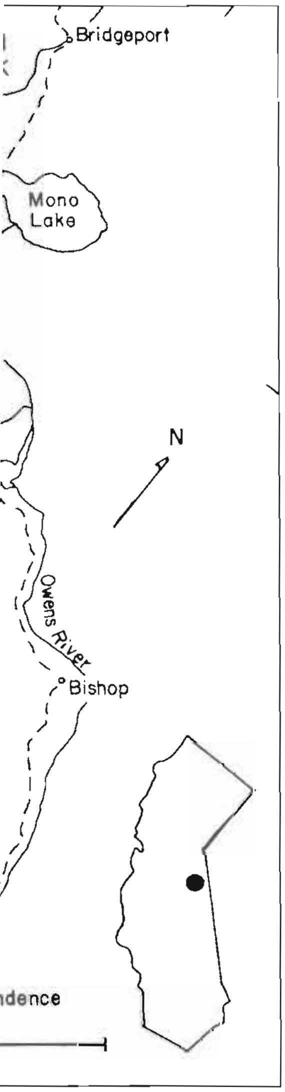

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TABLE 1

A Partial List of Eastern Sierra Nevada Glacial Deposits[a]

Glacial deposits	Relevant absolute ages
	9,800 ± 800 years[b]
Tioga	
Tenaya	
Tahoe	
	0.060 ± 0.050 my[c] 0.090 ± 0.090 my[c]
Mono Basin	
	0.062 ± 0.013 my[d]
Casa Diablo	
	0.126 ± 0.025 my[d] 0.710 my[e]
Sherwin	

[a] For details on the complete Sierra Nevada nomenclature see Sharp (1972) and references therein.

[b] Radiocarbon date on basal peat (Adam, 1967).

[c] Two K–Ar dates on a basalt flow that underlies till designated as Tahoe (Dalrymple, 1964).

[d] The most recent K–Ar dates on basalt flows that bracket Casa Diablo Till (Bailey *et al.*, 1976).

[e] Mean of K–Ar dates on Bishop Tuff that overlies Sherwin Till (Dalrymple and others, 1965).

have given preliminary comments on the entire glacial sequence; however, discussion herein will be limited to deposits presently designated as Tioga, Tenaya, Tahoe, Mono Basin, and Casa Diablo in age (Table 1). A major conclusion of our work is that our RD data support only a two-fold subdivision of post-Sherwin, pre-neoglacial deposits rather than the above five-fold subdivision.

Environmental Factors

The environmental factors which influence weathering rates and soil formation are similar for most valleys of this study (Table 2). The setting of the deposits in Sawmill Canyon (S) is atypical of the other three areas in that the deposits occur within the confines of the bedrock valley walls, and are vegetated by a mixed conifer forest with an understory of the Great Basin sage community. The deposits of the other three valleys lie beyond the range front and are generally occupied mostly by the Great Basin sage community.

Lithology is a most important variable which must be minimized if variations in RD data are to be considered time dependent. Weathering parameters are measured on medium- to coarse-grained granitic rocks. These usually are classified as granodiorite or quartz monzonite with a biotite content ranging from 4 to 8% (Kistler, 1966; Moore, 1963; Rinehart and Ross, 1964). In general, the rocks are similar enough in grain size and mineralogy that correlation based on RD techniques should

TABLE 2

Environmental Data for the Four Study Areas, Sierra Nevada

Locality	Elevation (m)	Granitic bedrock lithology[a]	Mean annual temp. (°C)	Mean annual[b] precipitation (cm)	Vegetation[b]
Sawmill Canyon (S)	2075–2635	granodiorite, quartz monzonite	7	35	mixed conifer forest, Great Basin sage community
Mammoth Creek	2270–2440	granodiorite, quartz monzonite	8	50	Great Basin sage community, Jeffery Pine forest
Sawmill Canyon (N)—Bloody Canyon	2195–2530	quartz monzonite	8	45	Great Basin sage community, mixed conifer forest
Green Creek	2225–2450	granodiorite	7	40	Great Basin sage community

[a] Taken from Moore (1963), Rinehart and Ross (1964), and Kistler (1966).

[b] Taken from U.S. Weather Bureau (1964), and Storer and Usinger (1963). Data given are interpolated for altitude from nearby weather stations and thus contain a ± error of unknown magnitude.

be possible from valley to valley (see Kistler, 1966; Moore, 1963; and Rinehart and Ross, 1964).

Relative-Dating Techniques

Of the many RD data that can be collected on morainal deposits, we collected only those that could be readily quantified and that showed the most promise for age differentiation based upon our prior experiences. A brief definition of our RD criteria follows, along with some potential problems. These definitions are taken or modified from Blackwelder (1931), Nelson (1954), Birman (1964), Sharp (1969, 1972), Birkeland (1973), Carroll (1974), and Shroba (1977).

Weathering Criteria: Moraine Surface Boulders

(1) Fresh-to-weathered ratio: Fifty boulders of at least 50-cm diameter are randomly selected at each site. A boulder is considered weathered if 50% or more of the exposed surface exhibits single grain mineral relief. A weathered boulder is rough to the touch and a fresh boulder feels smooth.

(2) Pitted-to-nonpitted ratio: Fifty boulders are counted at random and each is considered to be pitted if its surface has one or more concave depressions of more or less circular shape, apparently caused by granular disintegration. Pitting and weathering counts are made separately because boulders that are weathered are not necessarily pitted, and vice versa.

(3) Pit depth: The depth of a pit is measured from the bottom of the pit to the present surface of the boulder, and is thus a minimum measure of the amount of total pitting. Measurements are listed in the following two ways: (1) the maximum pit depth for the deposit, and (2) the average value for the deepest pits on the first 25 boulders classified as pitted.

Using a definition of weathering which combines our first three techniques, Clark (1967) found the exposure to wind and height above local vegetation to be strong controlling factors of boulder weathering. By selecting data collection sites along the flattest segments of moraine crests in the same kind of vegetational cover, we have attempted to reduce the variability of these controlling factors between data sets, within any single drainage.

(4) Maximum height of resistant mafic inclusion: The measurement here is the distance between the top of the inclusion and the average position of the adjacent rock surface.

(5) Rind-to-no rind ratio: A rind is a zone of weathered rock, recognized by a discoloration, that parallels the outer surface of the rock. For each count, 25 granitic cobbles are broken open and the presence or absence of a rind is recorded.

(6) Average rind thickness: In the above count each rind is measured to the nearest millimeter (0.1 mm for volcanic rocks), and, including the zeros, a mean rind thickness for the 25 clasts is calculated.

(7) Hammer-blow weathering ratio: At each site, 50 boulders are struck with a hammer and classified as fresh, weathered, or grusified. A boulder is fresh if it gives a sharp ringing sound, weathered if it gives a dull thud, and grusified if it disintegrates when struck. This method is less discriminating of age than the fresh-to-weathered technique described above.

(8) Surface boulder frequency (SBF): The total number of boulders with a diameter greater than 50 cm are counted within a 30- by 6-m rectangle along the crest of a moraine. In an effort to minimize the effect of boulder frequency variability along a single moraine, the rectangle is placed where there visually appears to be a maximum boulder concentration. Previous workers (Blackwelder, 1931; Sharp and Birman, 1963; Birman, 1964; Dickinson, 1968; and Sharp, 1969, 1972) relied in part on SBF to recognize and map glacial deposits of different age in the eastern Sierra Nevada. Our SBF data, however, do not allow us to make such distinctions. Reasons for the failure may be that too few counts were made by us, or that the 50-cm

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minimum diameter may have been too large. Other workers have used a 30-cm minimum diameter. A major problem with this technique is where to take such counts, as Rahm (1964) and Clark (1967) demonstrate that variation can be a function of original deposition. Our data do not resolve this problem.

(9) Granitic boulder-to-nongranitic boulder ratio: The measurement is made on 50 boulders greater than 50 cm in diameter. Nongranitic rock types are more resistant to weathering and should proportionally increase with time. Sharp (1969, 1972) found this technique useful when applied to a set of moraines along the same side of a single valley. We found the technique nondiscriminating, but as with SBF this may again result from too few counts to eliminate internal variation in the original deposit.

(10) Split-to-nonsplit ratio: At each site, 50 boulders are classified as split or nonsplit. A split boulder is one which appears to have broken along a planar crack since emplacement, by a mechanism other than spalling. This technique has been successfully applied in some areas of the Rocky Mountains (Shroba, 1977), but failed to discriminate among deposits in the present study.

(11) Oxidized-to-partially oxidized-to-unoxidized ratio: Fifty granitic boulders are classified on the basis of their surface discoloration. An oxidized boulder exhibits total surface discoloration (commonly 10 YR hues), a partially oxidized boulder is discolored to a lesser extent in either hue or surface area, and an unoxidized boulder exhibits no oxidation.

Weathering Criteria: Subsurface Features in Roadcuts or Hand-dug Pits

(12) Grusified granitic boulders: Below the ground surface, boulders with 30-cm diameter or greater are considered grusified if they exhibit intense granular disintegration throughout. Boulders are classified as either fresh, grusified and unoxidized, or grusified and oxidized.

(13) Soil properties: Soil properties are measured in the field and analyzed by standard laboratory techniques. Pits are dug along moraine crests in places considered to be free of excessive erosion or deposition. Field properties include horizonation, color, texture, consistence, structure, pH, and presence of other diagnostic pedologic features such as clay films or carbonate. Laboratory analyses are particle size distribution, percent loss on ignition (approximate organic matter), pH, and dry color. The soil horizon nomenclature follows Soil Survey Staff (1975) and Birkeland (1974). B horizon denotes a color B horizon, equivalent to a cambic horizon, and Bt denotes an increase in pedologic clay relative to the C horizon. Cox horizons are less oxidized than B horizons and numbered successively with increasing depth to denote diminishing degrees of oxidation. Roman numerals indicate various parent material layers.

An extensive literature documents the usefulness of soil stratigraphy in interpreting Quaternary deposits of the Sierra Nevada (Birkeland, 1964, 1967; Morrison, 1965; Janda, 1966; Janda and Croft, 1967; Curry, 1968, 1971; Birkeland and Janda, 1971; Shlemon, 1971; Harden and Marchand, 1977). Our soils data are often inconclusive and do not always support the age differentiation of other data. This could be due to some combination of the slow rate of weathering of granitic materials in the local climate, and the rate of removal by erosion of the uppermost soil horizons. We presently have no means of assessing the latter effect.

Moraine Morphology

(14) Width and slope angles: Although greatly controlled by unknown conditions of original deposition, the general cross-sectional shapes of moraines are measured in an attempt to describe the degree of preservation since deposition. The measurements taken are inner and outer slope angles, along with crest width. Although useful in the Rocky Mountains (Miller, 1971), the

measurements of this study did not produce a useful set of data for age differentiation; perhaps a more detailed shape analysis or sampling program is needed.

One important problem with some RD methods is that different workers cannot produce the same numbers, even though they are trying to use the same definition of the feature measured. We find that reproducibility between workers varies with the RD method. Within our own group of colleagues, we are reasonably consistent in measuring subsurface rock weathering and soil features. However, surface weathering features are more difficult to reproduce between workers. Therefore, all rock weathering data reported here were collected by Burke. Birkeland collected data on some parameters, and although his numbers differed from Burke's they resulted in the same weathering breaks and thus, the same subdivision of deposits.

Defining a Glaciation Using RD Techniques

Once the data are collected for a set of moraines the next task is to determine how much of a variation from one deposit to another constitutes a glaciation, and how much constitutes a stade. People working in Quaternary stratigraphy of glacial deposits probably can be grouped into the "splitters" and the "lumpers." Splitters would make the maximum subdivision of the sequence, probably at the stade level, based perhaps on subtle variations in weathering characteristics, on moraine position, and other features such as cross-cutting moraine relationships. Many unit names might be given these deposits, but because the variations in RD features from one deposit to the other are, at most, subtle, and cross-cutting relationships may only be of local significance, valley-to-valley correlation can be either difficult, nonexistant, or forced. Lumpers, on the other hand, require more gross changes in RD features before a subdivision is attempted; changes of enough magnitude that the major breaks in soil and weathering features can be consistently recognized by many workers from valley to valley. In this context, we are lumpers. The major question is how great a change in RD data is needed before we propose a new unit. No unique numerical change is adequate for all the data collected, but for many of the RD data on adjacent moraines we prefer a change by a factor of two in the numerical values before considering deposition to have occurred in different glaciations. Commonly, not all features will double or halve, and some will not change at all. However, because many factors can be invoked to suggest that most of the data collected are a minimum for the age of the till, those data of those RD methods that give the greatest differences between adjacent moraines might better reflect the true age differences. When the data are treated in this way, we probably are separating out first-order glaciations, rather than second-order fluctuations within first-order glaciations (Porter, 1971). It is these first-order features that can be recognized and correlated, and therefore deserve the assignment of formalized names.

GLACIAL DEPOSITS OF SAWMILL CANYON (S)

Introduction

Three workers have previously examined the glacial deposits in Sawmill Canyon (S). In a reconnaissance study, Knopf (1918) described deposits of two glaciations separated by an olivine basalt flow. He based the antiquity of the underlying till upon the dissection of the basalt, and noted that the overlying deposit was young because of "its ideal preservation" (Knopf, 1918, p. 31). Moore (1963) also recognized a twofold glacial sequence, and based upon a qualitative assessment of boulder weathering and the preservation of morainal form he correlated the prebasalt till with the Tahoe Glaciation and the postbasalt till with the Tioga Glaciation. Dalrymple (1964) recognized five ages of glacial deposits based upon relative position, degree of dissection, relative boulder frequency, and a granite-weathering ratio. However, his assignment of specific moraines to glaciations

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differs from that of Moore (1963), for Dalrymple (1964) assigned the prebasalt till a pre-Tahoe age and the oldest postbasalt till to the Tahoe. Thus his K–Ar basalt ages of 0.090 ± 0.090 my (KA970) and 0.060 ± 0.050 my (KA970A) (Dalrymple, 1964) were thought to provide a maximum limiting date on the Tahoe Glaciation.

Tioga Glaciation

Rather than three ages (Tioga, Tenaya, and Tahoe) as proposed by Dalrymple (1964), our data suggest that all of the postbasalt glacial deposits east of Sawmill Meadow were deposited during the same glaciation (Figs. 2 and 3, Tables 3 and 4). The similarities in weathering, pitting, and rind development among these three moraines is striking when compared to the prebasalt moraine. The boulders on all three deposits look relatively fresh with shallow weathering pits that do not exceed 35 mm. The rinds developed upon the granitic stones are spotty and difficult to recognize even though some are of a modest thickness. Soil profiles for the three

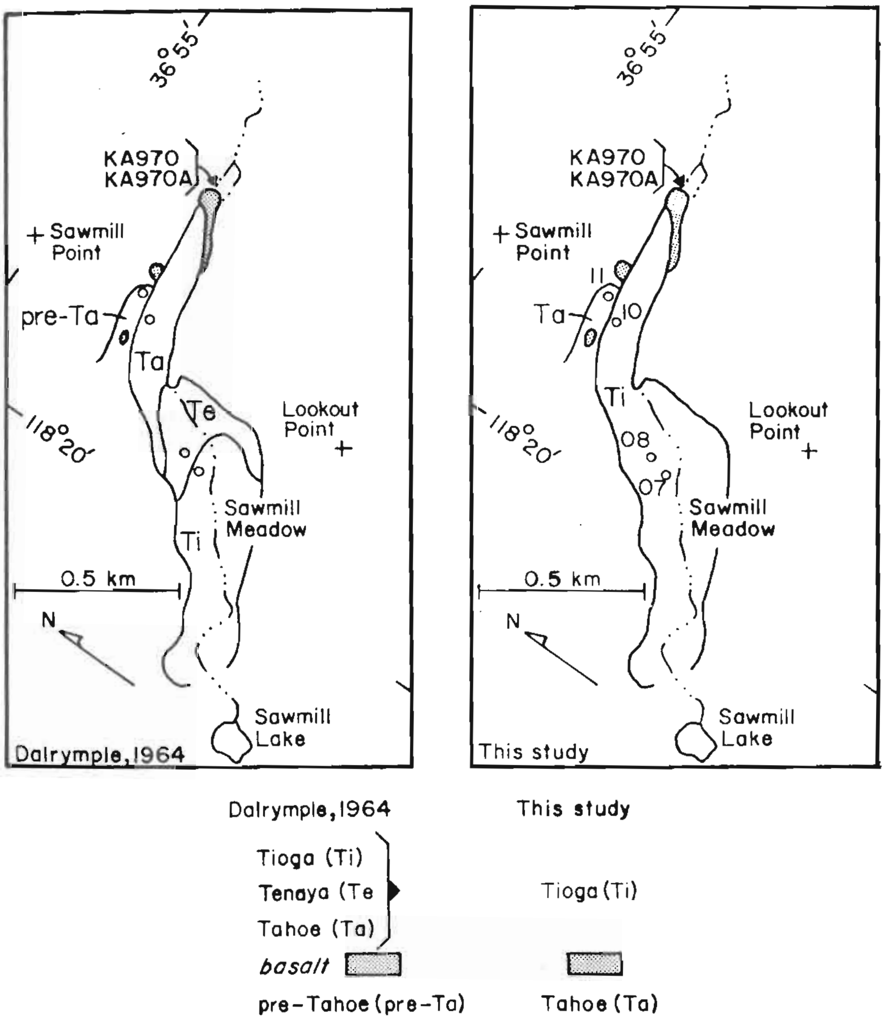

FIG. 2. Glacial deposits in Sawmill Canyon (S) according to Dalrymple (1964) and this study. In this and in the following figures, field localities are indicated by circles (O), site numbers are those used in the text and accompanying tables, and section corners are indicated by crosses(+). The location of the basalt dates is from Dalrymple (1964). The base map is the Mt. Pinchot 15-min quadrangle, California.

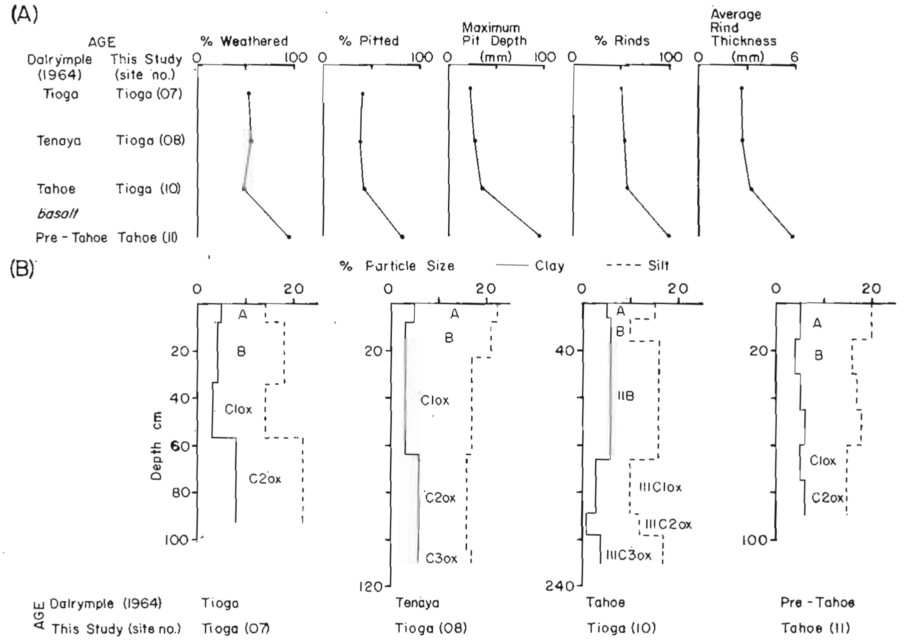

FIG. 3. (A) Selected RD and (B) soil data for deposits in Sawmill Canyon (S). Complete data and actual numbers are given in Tables 3 and 4.

moraines are nearly identical (Fig. 3b, Table 4). In general, the most intense oxidation color is 10 YR 5.5/3 which occurs in a poorly defined cambic B horizon. Very slight oxidation occurs below the B horizons and 2.5 Y colors extend to the base of the exposures. Particle-size distribution reveals no obvious trends related to age (Fig. 3b), but instead seem to reflect variations in parent material. Additionally, the lack of grusified boulders is a significant common feature of all three moraines.

The moraine resting directly upon the basalt (Site 10, Fig. 3a and Table 3) appears slightly more weathered than the other Tioga moraines. The weathering rinds are more easily recognized and a few percent of the small (10–15 cm) subsurface stones are grusified. The 132-cm depth to the base of the B horizon at site 10 is somewhat unusual for a Tioga age, but it seems to relate to geologic layering. The differences in RD data between this moraine and the moraines at sites 07 and 08 are very subtle, and we do not feel they justify a separate age assignment at this time. The site 10 moraine could, however, represent an early Tioga stade, or possibly what some investigators would regard as a Tenaya deposit.

Tahoe Glaciation

The only deposit which has surface data suggesting it to be significantly older than the Tioga Till is the prebasalt till (Site 11, Figs. 2 and 3 and Table 3). Relative to data for the postbasalt Tioga Tills, the percent of weathered boulders is seven times greater, the percent of pitted boulders, the mean thickness of granitic weathering rinds and the percent of boulders having rinds all double, and the maximum depth of pitting increases three-fold. Most soil data are similar to that for the Tioga Till (Fig. 3b and Table 4), except for the marked difference in the condition of granitic boulders between the postbasalt and prebasalt tills. Boulders up to 1 m in diameter within the soil of the prebasalt till are oxidized to yellowish-brown colors and intensely grusified so that they are easily cut through with a shovel.

The at-depth grusification of boulders in soils without intense pedological reddening or clay buildup and the advanced degree of weathering of surface boulders are characteristic of deposits commonly thought to be Tahoe in age.

Discussion

The data given here support Moore (1963) and suggest that two ages of till are represented in the deposits downvalley from Sawmill Meadow. The three post-basalt tills of Dalrymple (1964) are here correlated with the Tioga Glaciation, although the outermost one could be somewhat older. The prebasalt till has all the properties of Tahoe Till seen elsewhere along the eastern Sierra Nevada. Because of this, we suggest a revision of the unit boundaries (Fig. 2).

Significance of the Dates on the Basalt

Heretofore the dates of 0.090 ± 0.090 and 0.060 ± 0.050 my (Dalrymple, 1964) on the intertill basalt have been thought to provide a maximum age for the Tahoe Glaciation. The conclusion drawn here is that the basalt dates from the Tahoe–Tioga interglacial.

GLACIAL DEPOSITS ALONG MAMMOTH CREEK

Introduction

The Quaternary geology of the Mammoth Lakes area has been mapped in two previous studies. Rinehart and Ross (1964) mapped the moraines between Mammoth Lakes Village and Highway 395 (Fig. 4) as an undifferentiated unit which could tentatively correlate with any or all of the Tioga, Tahoe, and a pre-Tahoe, post-Sherwin deposit. Curry (1968, 1971) subdivided the major moraines into Tioga, Tenaya, Tahoe, and Mono Basin, but on his map they are shown only as Group B deposits. Curry (1971) also recognized an older till which he named the Casa Diablo. The type Casa Diablo Till lies between the lower and middle of three basalt flows originally dated at 0.441 ± 0.040 my (KA2098), 0.280 ± 0.067 my (KA2012), and 0.192 ± 0.035 my (KA1928) (Curry, 1971). Bailey and others (1976), however, have redated the lower and upper of the above mentioned three basalt flows at 0.126 ± 0.025 my (73G012) and 0.062 ± 0.013 my (73G014), and these latter ages are herein accepted as bracketing the Casa Diablo Till.

Tioga Glaciation

The RD data from our study do not permit any major subdivision of the post-Casa Diablo Tills, even though the text of Curry (1968, 1971) indicates that a four-fold subdivision of Tioga, Tenaya, Tahoe, and Mono Basin exists (Fig. 4 and 5a; Table 4). There is a suggestion of a progressive change of some RD values which generally agrees with stratigraphic position, but the presence of reversals in the trends confounds grouping the deposits into separate ages. Given this, subsurface data may be more satisfactory in differentiating the post-Casa Diablo tills. None of the deposits have grusified granitic boulders at depth, nor do the soils differ much one from another (Fig. 5b and Table 4). The soils consist of A/B/Cox profiles, and although they show an increase of clay content toward the surface, these increases are slight and could reflect the deposition of ash and other eolian material mixed with the tills. Therefore, based primarily upon the lack of subsurface grusification and progressive soil development we tentatively correlate all of Curry's (1971) Group B with the Tioga Glaciation.

Casa Diablo Glaciation

Surface exposure of Casa Diablo Till is limited, and the lack of true morainal form makes comparisons with the younger deposits difficult. Few surface data demonstrate that the Casa Diablo Till is much older than the Tioga Till of this study. Only the percent weathered granitic stones (Fig. 5a) and the maximum height of mafic inclusions (Table 3) show a clear separation of the Casa Diablo from the Tioga. In addition, the numerical values for these two weathering phenomena resemble Tahoe values of other drainages.

Subsurface data for the Casa Diablo Till do indicate an age greater than the Tioga. Many subsurface boulders are completely grusified, but the oxidation of the grus is

TABLE 3

WEATHERING AND MORPHOLOGICAL DATA FOR TILLS, EASTERN SIERRA NEVADA

	Age, site number														Moraine morphology		
Valley	This study	Original study	% Weathered	% pitted	Maximum pit depth (mm)	Average pit depth (mm)	Maximum height of mafic inclusions (mm)	% Rinds	Average rind thickness (mm)	Fresh: weathered: grus by hammer blow	SBF	% Granitic boulders[a]	% Split	Oxidized: partially ox: unoxidized[b]	Moraine width (m)	Distal slope (deg)	Proximal slope (deg)
Sawmill	Ti																
Canyon	07	Ti	52	40	23	—[c]	20	52	2.6	47:3:0	23	88	84	—	30–50	12	18
(S)	08	Te	52	38	28	—	20	56	2.8	46:4:0	40	86	60	20:30	8	22	25
			58	38	25	—	—	52	2.6	46:4:0	84	98	62	—	—	—	—
	10	Ta	54	40	35	—	15	48	3.0	48:2:0	66	94	52	11:42	3–4	29	30
			44	44	30	—	—	64	3.4	47:3:0	39	74	82	—	—	—	—
	Ta																
	11	pre-Ta	94	82	95	—	5	100	5.8	26:22:2	24	96	21	20:13	25–35	27	22
Mammoth	Ti																
Creek	20	Ti	10	34	35	—	—	44	2.8	50:0:0	80	78	24	—	—	—	—
			8	22													
	19	Te	7	6	10	—	—	—	—	34:0:0	58	2	—	—	7	15	22
	05	Ta	28	16	52	—	32	64	2.5	50:0:0	42	32	28	—	16	21	19
			28	20	53	—	—	—	—	50:0:0	89	44	24	—	—	—	—
	38	Ta	24	22	75	—	60	48	2.0	48:2:0	50	94	30	—		undefined	
			48	40													
	18	MB	20	42	57	—	40	68	3.1	46:4:0	91	82	26	—	5	17	25
			26	34													
	Ta																
	03	CD	71	33	65	—	122	88	2.8	21:3:0	13	42	22	—		undefined	
Sawmill	Ti																
Canyon	42	Ti	18	22	28	15	—	32	1.4	50:0:0	53	78	16	—	8	24	28
(N)—			12	22													
Bloody	43	Te	22	18	20	12	—	40	1.2	50:0:0	38	94	12	—	10	25	25
Canyon			12	16													

			26	34													
	Ta																
	03	CD	71	33	65	—	122	88	2.8	21:3:0	13	42	22	—		undefined	
Sawmill	Ti																
Canyon	42	Ti	18	22	28	15	—	32	1.4	50:0:0	53	78	16	—	8	24	28
(N)—			12	22													
Bloody	43	Te	22	18	20	12	—	40	1.2	50:0:0	38	94	12	—	10	25	25
Canyon			12	16													
	Ta																
	04	Ta															
	forested		62	26	80	15	—	76	2.9	45:5:0	33	76	32	5:31:14	15–20	22	27
			70	22	—	—	—	—	—	43:7:0	33	76	60	—	—	—	—
	40	Ta	80	68	120	30	—	80	4.2	43:6:1	43	84	26	2:33:15	20	20	26
			82	74													
	41	Ta	64	74	370	28	—	68	3.1	45:5:0	60	94	28	5:34:14	19	14	21
			82	80													
			74	62													
	01	MB	62	56	190	41	—	68	2.6	38:13:0	48	56	42	7:27:16	35–40	19	18
			64	52	—	—	—	72	3.1	37:13:0	66	68	42	—	20–25	16	20
			64	52													
Green	Ti																
Creek	45	Ti	16	42	65	14	—	48	1.9	47:3:0	103	84	10	1:14:35	—	—	—
	25	Ti	26	36	55	17	—	44	1.5	48:2:0	70	84	10	4:18:28	5–20	13	20
			20	34													
	Ta																
	24	Te	58	72	95	27	70	62	2.5	45:5:0	154	82	24	6:35:9	3	—	15
			52	60	—	31	—	60	2.6	47:3:0	77	90	10	7:31:12	—	—	—
			60	72													
			54	68													
	22	Ta	46	58	195	25	115	60	3.2	43:7:0	57	86	4	5:29:16	30	16	19
			50	72		26	—	56	2.6	46:4:0	—	92	16	—	—	—	—
			50	64													
			48	64													

[a] The nongranitic component consists of volcanic and metavolcanic rocks.

[b] Where only two numbers appear, the count was oxidized:unoxidized boulders only.

[c] A dash(—) represents no data available.

TABLE 4

SOIL DATA FOR TILLS IN THE EASTERN SIERRA NEVADA

Location	Site number	Age[a] Previous study	Age[a] This study	Horizons[b]	Depth (cm)	Color[c]	Texture[d]	Estimated % gravel	% < 2 mm fraction Sand	% < 2 mm fraction Silt	% < 2 mm fraction Clay	pH[e]	% Organic matter[f]	Remarks
Sawmill Canyon (S)	07	Ti	Ti	A	0–8	10 YR 3.5/2	LS	50–75	82	14	5	6.4	7	
				B	8–34	10 YR 5/3	LS	50–75	78	18	4	6.5	2	
				C1ox	34–57	2.5 Y 6/2	LS	50–75	82	14	3	6.4	1	
				C2ox	57–93+	2.5 Y 5/3	SL	50–75	70	22	8	6.2	2	
	08	Te	Ti	A	0–8	10 YR 3/2	SL	50–75	72	23	5	6.1	7	
				B	8–23	10 YR 5/3	LS	50–75	76	21	3	6.0	3	
				C1ox	23–64	2.5 Y 6/2	LS	50–75	80	17	3	6.1	1	
				C2ox	64–105	2.5 Y 6/2.5	LS	50–75	78	16	6	6.1	1	
				C3ox	105–115+	2.5 Y 5/4	LS	50–75	77	17	6	6.2	—	
	10	Ta	Ti	A	0–13	10 YR 6/3	LS	75	80	15	5	5.7	2	Depositional layering I, II, and III recognized on the basis of a change in size and percentage of gravel.
				B	13–32	10 YR 5/3.5	LS	75	84	10	6	6.0	1	
				IIB	32–132	10 YR 5/3	LS	50	78	16	6	6.2	1	
				IIIC1ox	132–179	2.5 Y 5/4	S	75	87	10	3	6.3	1	
				IIIC2ox	179–217	2.5 Y 6/2	S	75	87	12	1	6.3	1	
				IIIC3ox	217–231+	2.5 Y 7/3	LS	75	80	17	4	6.3	1	
	11	pre-Ta	Ta	A	0–15	10 YR 4/3	LS	90	76	20	5	6.6	4	Horizon boundaries are very difficult to determine, so sampled at 15-cm intervals rather than by horizons.
				B	15–30	10 YR 6/4	LS	90	80	16	4	6.8	2	
					30–45	10 YR 6/4	LS	90	78	17	5	6.8	1	
				C1ox	45–60	2.5 Y 5/3	LS	90	76	18	6	6.8	1	
					60–75	2.5 Y 5.5/3	LS	90	80	15	5	6.6	1	
				C2ox	75–90+	2.5 Y 5/3	LS	90	79	15	6	6.5	1	
Mammoth Creek	20	Ti	Ti	O	0–8	10 YR 4/2.5	LS	75	81	14	5	5.9	57	Depositional unit I appears to be largely extraneous material mixed with the till, unit II.
				IIA	8–16	10 YR 4/2	LS	75	79	17	4	6.1	3	
				IIA3	16–42	10 YR 4/3	LS	75	80	17	3	6.1	4	
				IIB	42–120	10 YR 5/3	LS	75	79	19	2	6.0	2	
				IICox	120–165+	10 YR 5/2	LS	75	79	19	2	6.0	2	
	19	Te	Ti	A	0–7	10 YR 4/2	LS	50–75	82	14	4	6.1	2	
				B	7–45	10 YR 3.5/3	LS	50–75	74	23	3	6.0	1	
				Cox	45–60+	2.5 Y 7/2	SL	50–75	69	28	3	6.2	0	
	05	Ta	Ti	A	0–11	10 YR 3/3	SL	75–90	72	23	5	5.9	1	The A and B horizons may have a slight admixture of eolian material.
				B	11–45	10 YR 4.5/4	SL	75–90	71	24	5	6.1	4	
				C1ox	45–90	2.5 Y 8/3	LS	75–90	76	22	2	6.2	1	
				C2ox	90–100	2.5 Y 7/4	LS	75–90	73	24	3	6.3	2	
				C3ox	100–116+	2.5 Y 7/3	SL	75–90	71	27	2	6.4	1	
	38	Ta	Ti	A1	0–8	10 YR 4/2	S	25	89	9	3	5.3	2	This is an end moraine and the low percentage of gravel is anomalous. Perhaps not comparable
				A3	8–20	10 YR 4/3	LS	10	82	14	4	5.7	3	
				B1	20–35	10 YR 5/3	LS	10	80	15	5	6.0	2	
				B2	35–70	10 YR 5/3.5	SL	10	74	20	6	6.1	2	

						2.5 Y 5/3	LS	90	79	15	6	6.5	1	rather than by horizons.
Mammoth Creek	20	Ti	Ti	O	0–8	10 YR 4/2.5	LS	75	81	14	5	5.9	57	Depositional unit I appears to be largely extraneous material mixed with the till, unit II.
				IIA	8–16	10 YR 4/2	LS	75	79	17	4	6.1	3	
				IIA3	16–42	10 YR 4/3	LS	75	80	17	3	6.1	4	
				IIB	42–120	10 YR 5/3	LS	75	79	19	2	6.0	2	
				IICox	120–165+	10 YR 5/2	LS	75	79	19	2	6.0	2	
	19	Te	Ti	A	0–7	10 YR 4/2	LS	50–75	82	14	4	6.1	2	
				B	7–45	10 YR 3.5/3	LS	50–75	74	23	3	6.0	1	
				Cox	45–60+	2.5 Y 7/2	SL	50–75	69	28	3	6.2	0	
	05	Ta	Ti	A	0–11	10 YR 3/3	SL	75–90	72	23	5	5.9	1	The A and B horizons may have a slight admixture of eolian material.
				B	11–45	10 YR 4.5/4	SL	75–90	71	24	5	6.1	4	
				C1ox	45–90	2.5 Y 8/3	LS	75–90	76	22	2	6.2	1	
				C2ox	90–100	2.5 Y 7/4	LS	75–90	73	24	3	6.3	2	
				C3ox	100–116+	2.5 Y 7/3	SL	75–90	71	27	2	6.4	1	
	38	Ta	Ti	A1	0–8	10 YR 4/2	S	25	89	9	3	5.3	2	This is an end moraine and the low percentage of gravel is anomalous. Perhaps not comparable to other soils because of parent material variation.
				A3	8–20	10 YR 4/3	LS	10	82	14	4	5.7	3	
				B1	20–35	10 YR 5/3	LS	10	80	15	5	6.0	2	
				B2	35–70	10 YR 5/3.5	SL	10	74	20	6	6.1	2	
				Cox	70–140+	2.5 Y 6.5/3	LS	10	77	20	3	6.3	2	
	18	MB	Ti	A1	0–6	10 YR 4/2.5	SL	75	69	25	6	6.3	6	Carbonate content in the bottom three horizons is 1, 9, and 8%, respectively. The origin and possible age significance remains unknown.
				A3	6–25	10 YR 4/3	SL	75	67	27	7	6.4	5	
				B2	25–46	10 YR 6/3	LS	50–75	74	24	2	6.4	2	
				B3	46–68	10 YR 5.5/4	LS	50–75	78	21	2	6.5	0	
				C1oxca	68–90	2.5 Y 6/3	LS	50–75	75	20	5	6.7	1	
				C2oxca	90–95+	2.5 Y 5.5/3	LS	50–75	74	20	6	7.0	2	
	03	CD	Ta	A	0–8	10 YR 5/2	SL	80–95	74	17	8	6.4	3	This is the type locality of Casa Diablo Till. B2t has clay skins on ped faces. "Fr till" is fresh till sampled from nearby roadcut.
				B1	8–23	10 YR 5/3	SL	80–95	72	20	8	6.4	2	
				B2t	23–88	10 YR 6/4	SL	80–95	57	29	14	6.5	3	
				Cox	88–129	10 YR 7/4	SL	50–75	62	30	8	6.4	2	
				Cn	129–135+	2.5 Y 6/3	SL	50–75	63	30	7	6.5	2	
				Fr till	about 500	5 Y 7/2	SL		60	35	5	6.5	4	
	39	CD	Ta	A	0–29	10 YR 4/3	LS	50	80	12	7	6.5	4	Site has a 12° slope making comparison to other soils questionable.
				B2	29–77	7.5 YR 5/4	SL	50	73	18	9	6.7	4	
				B3	77–137	7.5 YR 5/3	LS	75	81	12	7	6.6	2	
				C1ox	137–174	10 YR 5/3.5	LS	75	82	12	6	6.5	1	
				C2ox	174–199+	2.5 Y 5/3	LS	75	85	12	3	6.6	2	
	42	Ti	Ti	A	0–12	10 YR 6/3.5	LS	75–90	77	19	4	5.7	4	The A horizon appears to have an eolian ash (?) mixed with the till.
				IIB	12–25	10 YR 7/2.5	SL	75	65	32	3	6.3	1	
				IICox	25–102+	10 YR 7/2 to 2.5 Y 7/2	LS	75	72	27	1	6.5	0	
Sawmill Canyon (N)—Bloody Canyon	43	Te	Ti	A	0–10	10 YR 4.5/3	LS	50	78	17	5	5.6	12	The A horizon appears to have an eolian ash (?) mixed with the till. The IICox is indurated by silica (?) cement.
				IIB	10–25	10 YR 5.5/3	SL	50	70	25	5	6.3	2	
				IICox	25–120+	10 YR 7/2.5 to 2.5 Y 7/2	LS	50	68	29	3	6.5	0	
	04	Ta	Ta	A	0–8	10 YR 6/3	SL	75–90	71	24	6	5.8	2	A and B horizons appear to have eolian ash (?) mixed with the till. Cox horizons are slightly indurated by silica (?) cement.
				B	8–20	10 YR 7/3	SL	75–90	74	20	6	5.5	1	
				IIC1ox	20–64	2.5 Y 7/3	LS	75–90	83	13	4	5.6	0	
				IIC2ox	64–120+	2.5 Y 8/2.5	LS	75–90	75	22	3	5.5	0	
	01	MB	Ta	A	0–7	2.5 Y 6/3	SL	75–90	70	27	4	6.2	2	This is the type locality of Mono Basin Till. Entire comment from site 04 applies here also.
				B	7–20	10 YR 6/3	SL	75–90	66	27	7	6.5	1	
				C1ox	20–80	10 YR 7/3 to 2.5 Y 7/3	SL	75–90	64	31	6	6.5	1	
				C2ox	80–107+	2.5 Y 7.5/2	SL	75–90	63	33	4	6.5	0	

TABLE 4—(*Continued*)

Location	Site number	Age[a] Previous study	Age[a] This study	Horizons[b]	Depth (cm)	Color[c]	Texture[d]	Estimated % gravel	% < 2 mm fraction Sand	% < 2 mm fraction Silt	% < 2 mm fraction Clay	pH[e]	% Organic matter[f]	Remarks
	02	MB	Ta	A	0–10	2.5 Y 7/2.5	SL	50–75	61	33	6	6.6	1	Same moraine as site 01, with same comments applying.
				B	10–43	10 YR 8/3	SL	75–90	75	19	6	6.6	1	
				IIC1ox	43–88	10 YR 8/2	LS	90	77	17	6	6.2	1	
				IIC2ox	88–115+	2.5 Y 8/2	LS	90	76	19	5	6.3	0	
Green Creek	25	Ti	Ti	A	0–20	10 YR 4/3	SL	75–90	67	27	6	7.0	5	Upper portion of profile may have slight eolian influx.
				B	20–50	10 YR 5/3	SL	75–90	74	21	5	6.9	1	
				Cox	50–150	2.5 Y 6/3	LS	75–90	75	20	4	6.6	1	
				Cn	150–165+	5 Y 7/2.5	SL	75–90	73	24	3	6.5	0	
	45	Ti	Ti	A	0–23	10 YR 5/3.5	SL	50	65	30	5	6.0	2	
				B	23–45	10 YR 5/4	SL	50	66	29	5	6.5	1	
				Cox	45–155	10 YR 6/3.5	LS	50	73	24	3	6.7	0	
				Cn	155–185+	2.5 Y 6/3.5	LS	50	74	24	2	6.9	0	
	24	Te	Ta	A	0–14	10 YR 4.5/3	SL	50–75	72	23	5	6.0	3	
				B1	14–29	10 YR 5/3.5	SL	50–75	71	24	5	6.3	1	
				B2	29–50	10 YR 6/4	SL	50–75	71	25	4	6.7	0	
				B3	50–68	2.5 Y 6/3	LS	50–75	74	22	3	6.8	0	
				Cox	68–93	2.5 Y 7.5/3	SL	50–75	72	24	4	6.8	0	
				Cn	93+	5 Y 7/2	LS	50–75	80	18	2	7.1	0	
	22	Ta	Ta	A	0–8	10 YR 5.5/3	SL	50–75	69	25	6	6.3	2	Cn (?) may be a C2ox horizon.
				B	8–30	10 YR 5/4	LS	50–75	76	19	6	7.0	1	
				Cox	30–94	2.5 Y 6/3	LS	50–75	77	19	4	7.2	0	
				Cn(?)	94–130+	2.5 Y 8/2	LS	50–75	78	19	3	7.9	0	

[a] Age of previous study is based upon works of Dalrymple (1964)—Sawmill Canyon (S), Curry (1971)—Mammoth Creek, Sharp and Birman (1963)—Sawmill Canyon (N)—Bloody Canyon, and Sharp (1972)—Green Creek. Age assignments are Tioga (Ti), Tenaya (Te), Tahoe (Ta), Mono Basin (MB), and Casa Diablo (CD).

[b] Nomenclature follows Soil Survey Staff (1975) and Birkeland (1974).

[c] Colors are dry, determined on less than 2-mm fraction.

[d] Textural designations are loamy sand (LS), sandy loam (SL), and sand (S).

[e] pH determinations are by meter on a 2:1 water to soil mixture.

[f] Organic matter determined by loss on ignition, corrected for structural water loss by subtracting loss on ignition of organic free silt + clay fraction.

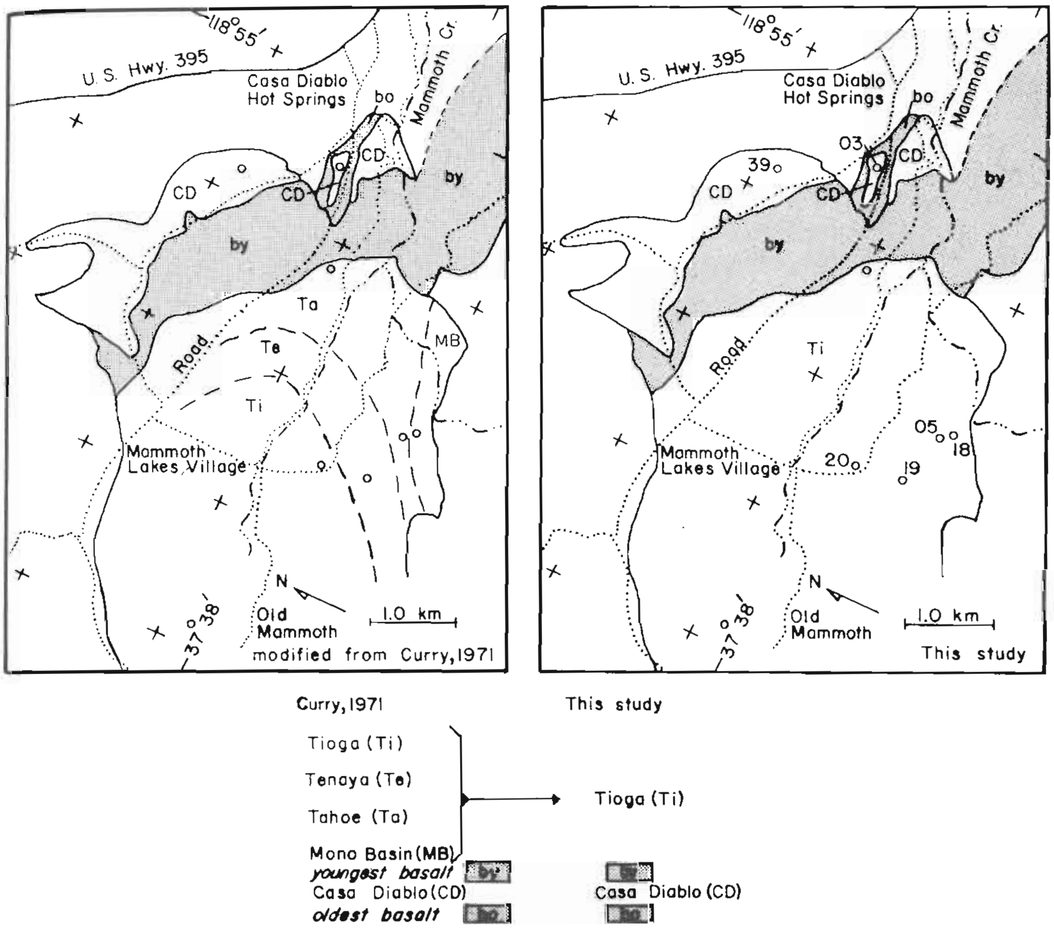

FIG. 4. Glacial deposits along Mammoth Creek according to Curry (1971) and this study. The age boundaries for Curry (1971) are an approximation taken from his text, as he maps all post-Casa Diablo Tills as Group B. The basalts shown are the youngest and oldest of those mapped by Curry (1971), and are the flows dated by Bailey and others (1976). The base map is the Mt. Morrison 15-min quadrangle, California.

slight. In addition, the soil has the strongest textural B horizon development within the study area for post-Sherwin tills. The 6% clay increase from the Cox to the B2t horizon is thought to be pedogenic because of both the color and the presence of clay films (Site 03, Fig. 5b and Table 4). The clay increase is greater than other soils in the eastern Sierra Nevada thought by us to be of similar age. Weathering-rind data collected from near the top of the B horizon also corroborate the above subdivision based on soil and grusification data (Table 5). These data all suggest that the Casa Diablo Till has many characteristics similar to the Tahoe elsewhere.

The lack of morainal form in the Casa Diablo Till may suggest to some workers a pre-Tahoe age. However, even the Tioga moraines along this creek show only a low rolling relief. As noted by Rinehart and Ross (1964), the deposits near Mammoth Lakes resulted from a piedmont type ice flow that gave rise to this low-relief morainal morphology.

Discussion

The two age groups of tills along Mammoth Creek seem to correlate best with the Tioga and Tahoe Glaciations. All post-Casa Diablo deposits have subsurface weathering and soil parameters that are consistent

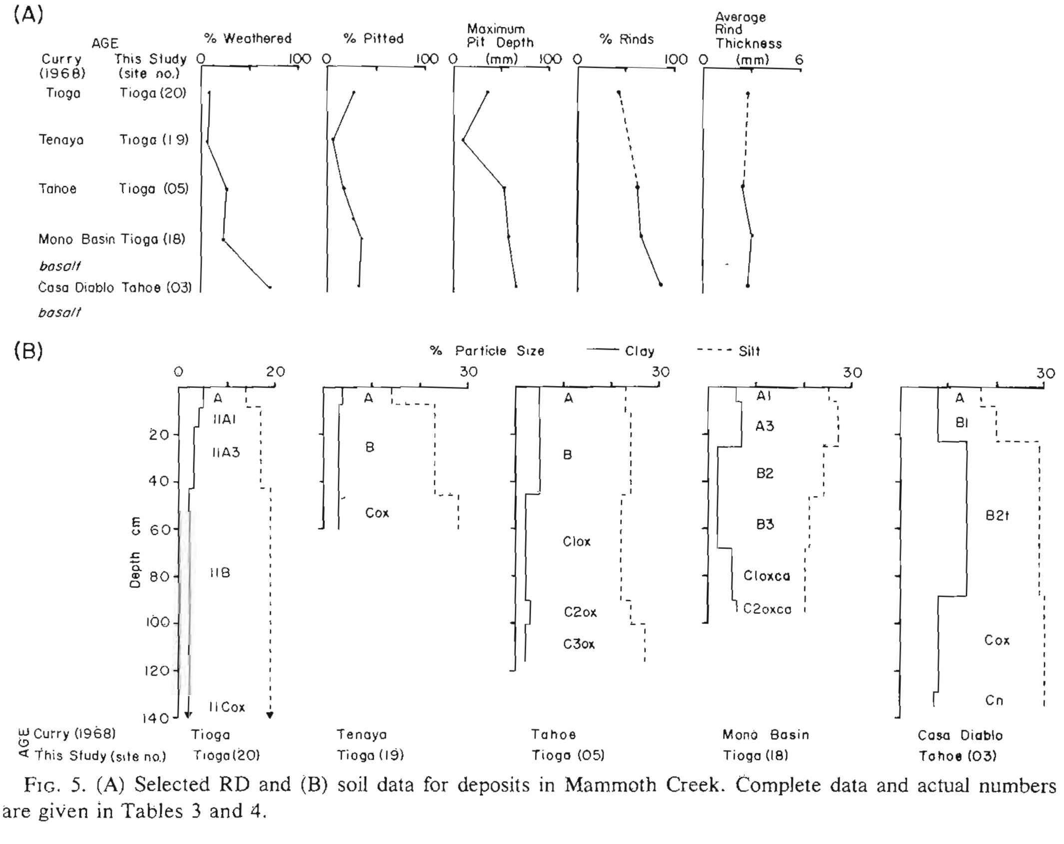

FIG. 5. (A) Selected RD and (B) soil data for deposits in Mammoth Creek. Complete data and actual numbers are given in Tables 3 and 4.

with a Tioga age. Some surface data suggest that the outermost Tioga moraines are somewhat older, and the possibility exists that they could be the Tenaya of other workers. We are, however, not satisfied with such an interpretation because of some trend reversals in the data for post-Casa Diablo tills, and several possibilities exist to explain these reversals. One is that the moraines were sampled near their terminal position, and it has been shown elsewhere that RD data are more variable in terminal moraines than in lateral moraines (Janda, 1966; McCulloch, 1963; Sharp, 1969, 1972). Another is that because the deposits are close to the lower limit of trees, past fires may confound some of the surface weathering data. Furthermore, all along Mammoth Creek, a question exists as to the degree to which burial, redistribution, and erosional stripping of volcanic material influenced surficial weathering. Finally, as in every drainage in this study one could argue that we do not have data from a sufficient number of sample sites. These same factors could account for the lack of differentiation between Casa Diablo and post-Casa Diablo tills on surface-weathering data. Hence,

TABLE 5

DATA ON WEATHERING RINDS IN THE MAMMOTH LAKES AREA[a]

Age of moraine[b]	Mean rind thickness (mm) basalt	Mean rind thickness (mm) quartzite
Tioga	0.23	0.21
Tenaya	0.17	0.25
Tahoe	0.26	0.18
Casa Diablo	0.50	0.50

[a] From Colman (1977).

[b] Age according to Curry (1971).

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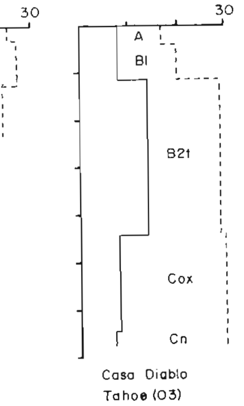

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this area can be used as an example of where the usefulness of subsurface RD data outweighs the usefulness of surface RD data for age differentiation.

The Casa Diablo soil has the strongest development for Tahoe equivalent soils in this portion of the eastern Sierra Nevada. Although the possibility exists that Casa Diablo is pre-Tahoe, some local factors may help account for the 6% clay increase in this profile and its absence in other Tahoe profiles. Volcanic lithologies are common in this drainage and these would have higher rates of clay production than would granitic lithologies. Tephra deposits mantle much of the topography and these could weather rapidly to clay which could infiltrate into the soil. Yet another factor is that the parent material is initially slightly higher in clay content than are most eastern Sierra Nevada tills and this alone would promote faster clay production (Birkeland, 1974). Finally, a somewhat higher precipitation than is present in other drainages (Table 2) could accelerate the rate of clay production. If it is accepted from the soil, grusification, and rind data for volcanic clasts that the Casa Diablo Till is probably of Tahoe age, then the 6% clay increase from the Cox to the Bt horizon is a maximum for post-Tahoe soils in this part of the eastern Sierra Nevada.

The Casa Diablo–Tahoe correlation based on our RD data suggests that a portion of Tahoe Glaciation occurred between 0.062 ± 0.013 and 0.126 ± 0.025 my ago. On the other hand, if the Casa Diablo Till is older than the Tahoe, the bracketing dates require that Tahoe deposits are either (1) missing along Mammoth Creek, or (2) within the oldest of Curry's Group B moraines. However, our RD data suggest that Curry's Group B moraines are indeed an undifferentiated unit which correlates with the Tioga Glaciation. Furthermore, there are no compelling reasons why Tahoe till should not be present in the area studied. Therefore, we accept the new Casa Diablo dates, and feel the RD data support the Casa Diablo–Tahoe correlation, as well as the Group B–Tioga correlation.

GLACIAL DEPOSITS OF SAWMILL CANYON (N)—BLOODY CANYON

Introduction

The cross-cutting and nested morphological relationships of moraines along Sawmill Canyon (N)—Bloody Canyon (Figs. 6 and 7) have long been discussed (McGee, 1885; Russell, 1887; Putnam, 1949). Sharp and Birman (1963) subdivided these moraines using semiquantitative data into a four-fold subdivision of Mono Basin, Tahoe, Tenaya, and Tioga. This valley contains the type locality of Mono Basin Till and one of the first Tenaya Tills described east of the Sierra Nevada crest. In contrast, Putnam (1949, p. 1291) and Kistler (1966) recognized only Tioga and Tahoe deposits, and this is in line with our conclusions.

Tioga Glaciation

The small sharp-crested moraines along Walker Creek—the Tioga and Tenaya of Sharp and Birman (1963)—which are superposed on the inner slopes of the massive Tahoe moraines (Fig. 6) can be demonstrated by RD data to be quite similar to each other and significantly younger than the Tahoe moraine (Fig. 8a and Table 3). Weathering data are consistent between the post-Tahoe moraines and all values are at least half those for the Tahoe deposits. The soils developed upon the two post-Tahoe moraines are nearly identical (Fig. 8b and Table 4). Both soils have a thin surficial layer of ash mixed with till which in turn overlies till. Particle-size analyses show no obvious pedogenic clay buildup; however, the very slight clay increase toward the top of the profiles could result from weathering, or it could reflect eolian influx. Granitic boulders are fresh throughout the soils.

Tahoe Glaciation

In order to compare the Tahoe and the Mono Basin Tills of Sharp and Birman (1963), the following data collection sites

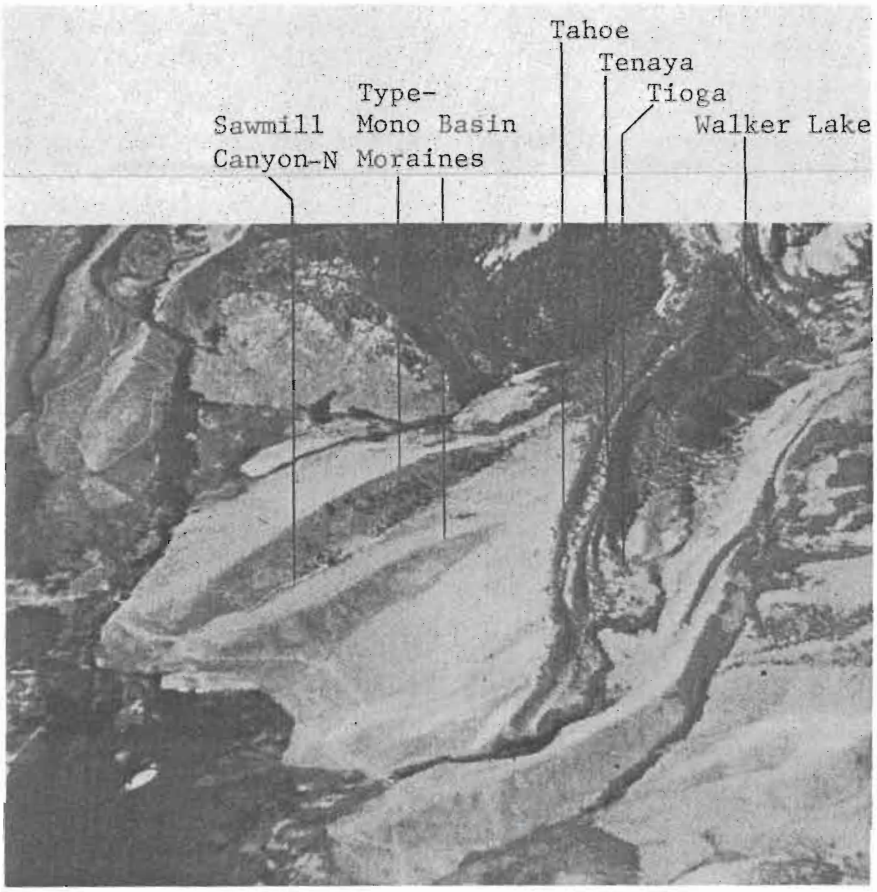

FIG. 6. Moraines of the Sawmill Canyon (N)—Bloody Canyon area, illustrating the cross-cutting relationships of the Mono Basin and Tahoe moraines and the nested relationships of the Tahoe and younger moraines. Age assignments from Sharp and Birman (1963).

were established: (1) Two sites (01 and 02) in sagebrush vegetation on the right lateral type Mono Basin moraine; (2) one site (04) in forest vegetation on the major right lateral Tahoe moraine; (3) one site (40) in sagebrush vegetation on the same Tahoe moraine as site 04; and (4) one site (41) in sagebrush vegetation on a smaller Tahoe lateral moraine (Fig. 7). These vegetational differences are considered crucial to our interpretation of the ages of the deposits.

If one compares certain RD data for the sage-covered type Mono Basin moraine with similar data for the forested Tahoe moraine, an apparent age difference may be argued (Fig 8a). However, for reasons given below, surface RD data should be compared only when collected under similar vegetation. The best comparative data in this study are for nonforested conditions. Indeed, comparisons of RD data collected from comparable sage-covered sites on Mono Basin and Tahoe moraines suggest that the age difference between these landforms is not great, in spite of their pronounced cross-cutting relationships. We believe that spalling related to past forest fires could explain the different values derived for forested and sage-covered sites along the Tahoe moraine. As has been suggested by Blackwelder (1927) and demonstrated in stratigraphic studies by Birkeland (1973)

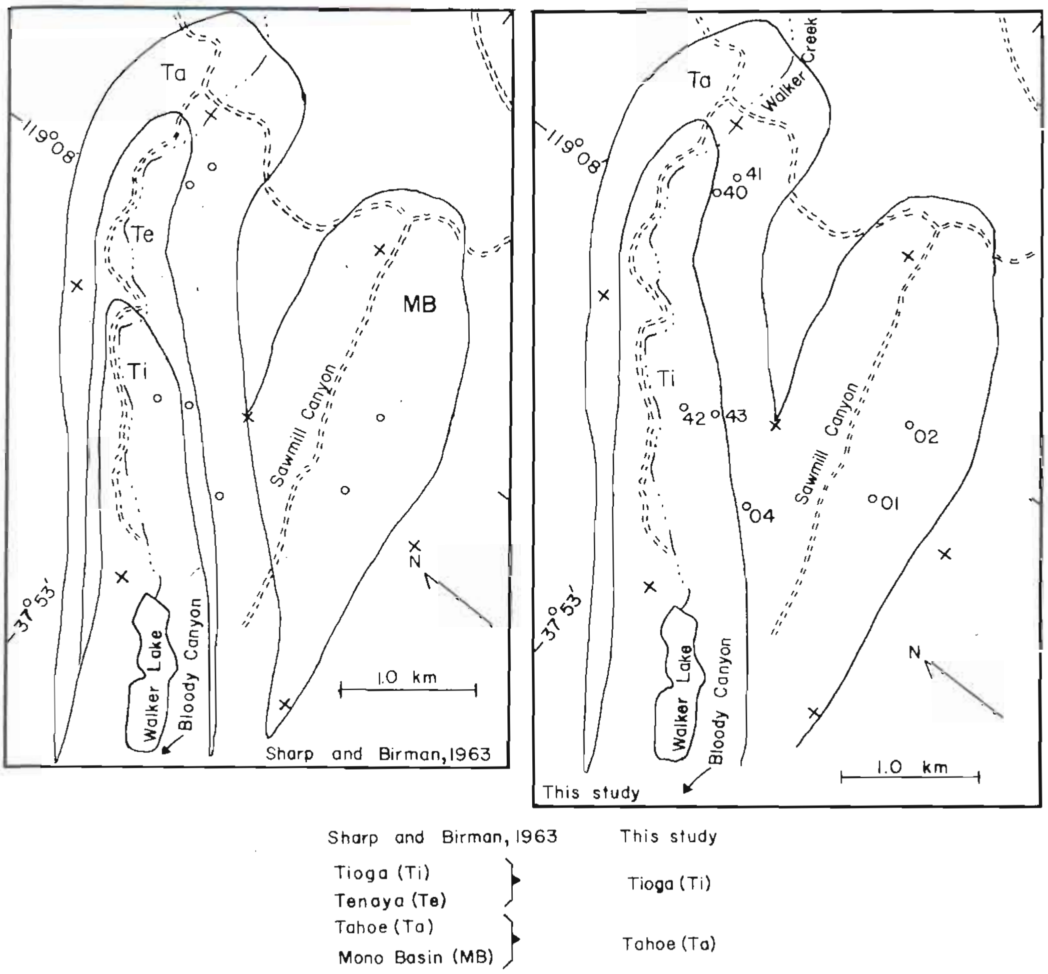

FIG. 7. Glacial deposits in the Sawmill Canyon (N)—Bloody Canyon area according to Sharp and Birman (1963) and this study. The base map is the Mono Craters 15-min quadrangle, California.

and Meierding (1977), forest fires limit the usefulness of comparing surface weathering data between forested and nonforested areas. The atypical weathering data of the forested Tahoe moraine is probably due to the freshing effect brought about by the spalling of boulders during ancient forest fires. This is supported by the high probability of a past fire history along the eastern Sierra Nevada (Schroeder and Buck, 1970).

Subsurface data do not suggest a great difference in age between the Mono Basin and Tahoe tills. The post-Mono Basin soil has been discussed previously by Birkeland and Janda (1971), and they stated that it does not have properties which indicate a greater age than the nearby post-Tahoe soil (Birkeland and Janda, written communication *in* Wahrhaftig and Sharp, 1965, p. 84). The data here suggest that soil development in both Mono Basin and Tahoe Tills is minimal. One post-Mono Basin profile (site 01) exhibits a very slight clay increase in the B horizon, but the other does not (Fig. 8b). For comparison, the soil in Tahoe Till also has a very slight clay increase in the A and B horizons, relative to the Cox horizons. These clay increases are believed to repre-

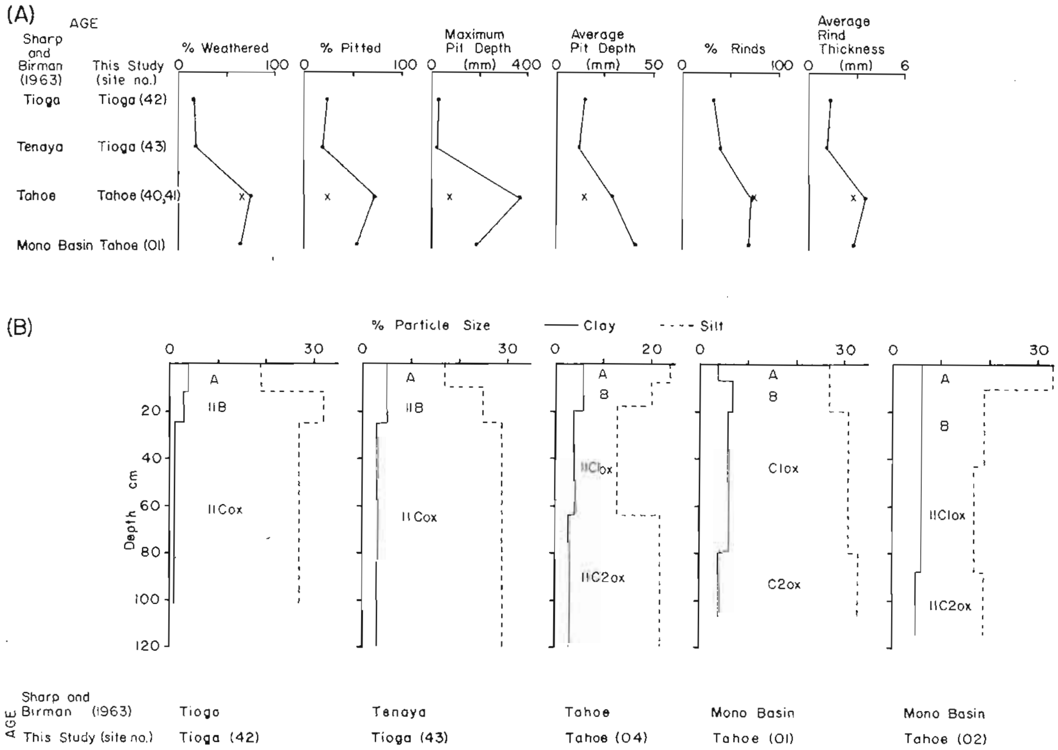

FIG. 8. (A) Selected RD and (B) soil data for deposits in the Sawmill Canyon (N)—Bloody Canyon area. Complete data and actual numbers are given in Tables 3 and 4. The x in (A) represents data for site 04 on the forested portion of the major Tahoe moraine.

sent some combination of eolian influx and *in situ* weathering. Neither the Mono Basin nor Tahoe Tills have good exposures; however, the soil pit of site 02 on the Mono Basin moraine has a 50-cm boulder which is totally grusified and weakly oxidized, and smaller boulders in both moraines are commonly grusified. Thus, because both Tahoe and Mono Basin deposits have weak soil development and partial grusification, the deposits cannot be differentiated on the basis of subsurface parameters.

The morphology of the Mono Basin moraines appears to be the only criteria which may support a significant time difference between Mono Basin and Tahoe deposits. Although slopes are similar, the Mono Basin moraine has a wider crest than the Tahoe moraine (Table 3). In addition, a skyline profile of the two moraines (Fig. 9) shows the Mono Basin moraines to have less relief than Tahoe moraines, and this may suggest smoothing with time. In summary, whereas some morphologic data suggest a time break between the Mono Basin and Tahoe moraines, our RD and soil data do not adequately demonstrate two mappable units.

Two other lines of reasoning deserve mentioning for they have been used to support a relatively large hiatus between the times of Mono Basin and Tahoe deposition. One line of reasoning is the time reportedly needed for Walker Creek to breach the left-lateral Mono Basin moraine so that younger glacial advances went to the northeast rather than following the path of Mono Basin ice. Sharp and Birman (1963, p. 1084) state:

> That the Tahoe laterals are superimposed across the upper ends of the abandoned moraines of Sawmill Canyon is adequate testimony to a considerable age difference.

We would like to suggest that moraine breaching could be accomplished while ice

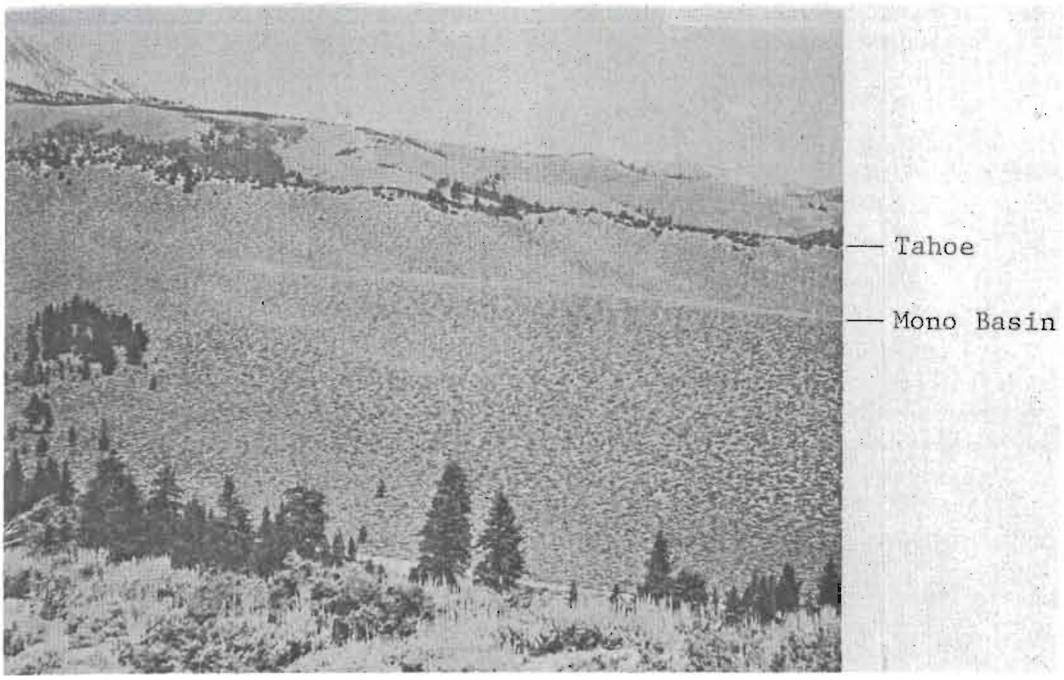

FIG. 9. Skyline profile of the Mono Basin and Tahoe moraines as defined by Sharp and Birman (1963). The photo was taken from the right lateral Mono Basin moraine, Walker Creek lies beyond the Tahoe moraine.

occupies the valley, thus allowing ice-marginal streams to overtop and cut through lateral moraines. After the ice snout retreated above the Tahoe breach, readvance could be channeled to the northeast. A second line of reasoning proposed by Curry (1968) and Clark (1972) suggests enough time to allow for a vertical fault motion of about 120 m (Curry) and 60 m (Clark) between Mono Basin and Tahoe deposition. The evidence for postulated faulting is indirect, and the time required for the proposed offset is unknown. As important as these lines of reasoning are, we do not feel they are presently as conclusive as our RD data for delineating separate mapping units.

Discussion

The RD data given here suggest that only two glacial deposits of different age are present. The confidence of this statement is strengthened by the fact that most of the data collected seem to point to the same conclusion. Confidence would be increased, however, if we had more data on subsurface granitic clast weathering. The previously mapped Tenaya seems best included with the Tioga. There is, however, more of a problem with the Tahoe and the Mono Basin. If both are studied under similar vegetation covers, they are quite similar; they only look dissimilar when the forested Tahoe is compared with the sagebrush-covered Mono Basin. One problem though is that the sagebrush-covered Tahoe moraines are near the terminal positions, and it was argued earlier that clasts in these positions might be more weathered than clasts in lateral moraines of the same age. At the present time, we cannot solve these arguments without extensive trenching, but we do know that fire can be an important factor in destroying surface weathering features. Unfortunately, the transition from forest to sage takes place at about the same position as one might expect the "terminal" effect to show up. At the present time, we consider the fire hypothesis to be the most plausible and so group the Mono Basin and Tahoe into the Tahoe Glaciation, and suggest a change of Sharp and Birman's (1963) unit boundaries as shown in Fig. 7. The cross-cutting relationships could, in this case, be used to show the duration of the Tahoe instead of an indication of two different glaciations.

GLACIAL DEPOSITS OF GREEN CREEK

Introduction

The glacial deposits of Bridgeport Basin have been mapped in part by Blackwelder (1931) and in detail by Sharp (1972). In the Green Creek drainage, Blackwelder recognized tills of the Tioga, Tahoe, and Sherwin Glaciations but gave little data in support of the three age assignments. Sharp (1972), on the basis of field relationships and semiquantitative weathering data recognized five ages of till—Tioga, Tenaya, Tahoe, Mono Basin, and Sherwin (Fig. 10), and much of this is supported by the work of Dickinson's group (1968).

Tioga Glaciation

Two moraines assigned to the Tioga Glaciation by Sharp (1972) were selected for our study (Fig. 10). The RD parameters which have been shown to delineate weathering breaks most consistently in other valleys, as well as surface oxidation data, indicate that both sites are of the same age (Fig. 11a and Table 3).

Soils for these two moraines are similar, both being weakly developed A/B/Cox pro-

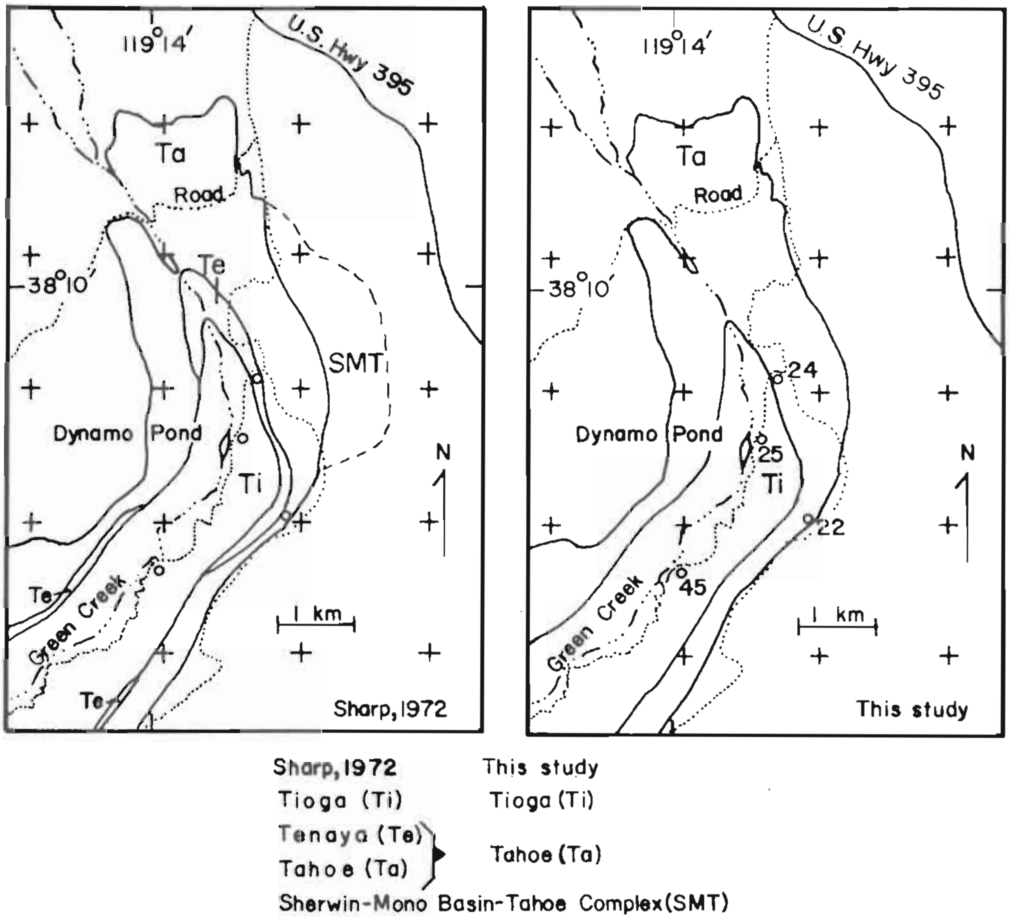

FIG. 10. Glacial deposits along Green Creek according to Sharp (1972) and this study. The "SMT" unit is not shown on the right hand map because not enough work was done on it. The base map is the Bodie 15-min quadrangle, California.

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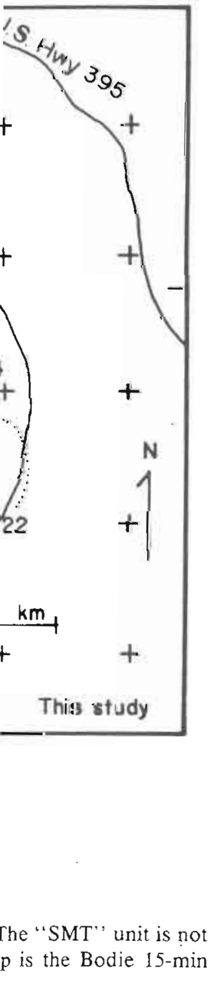

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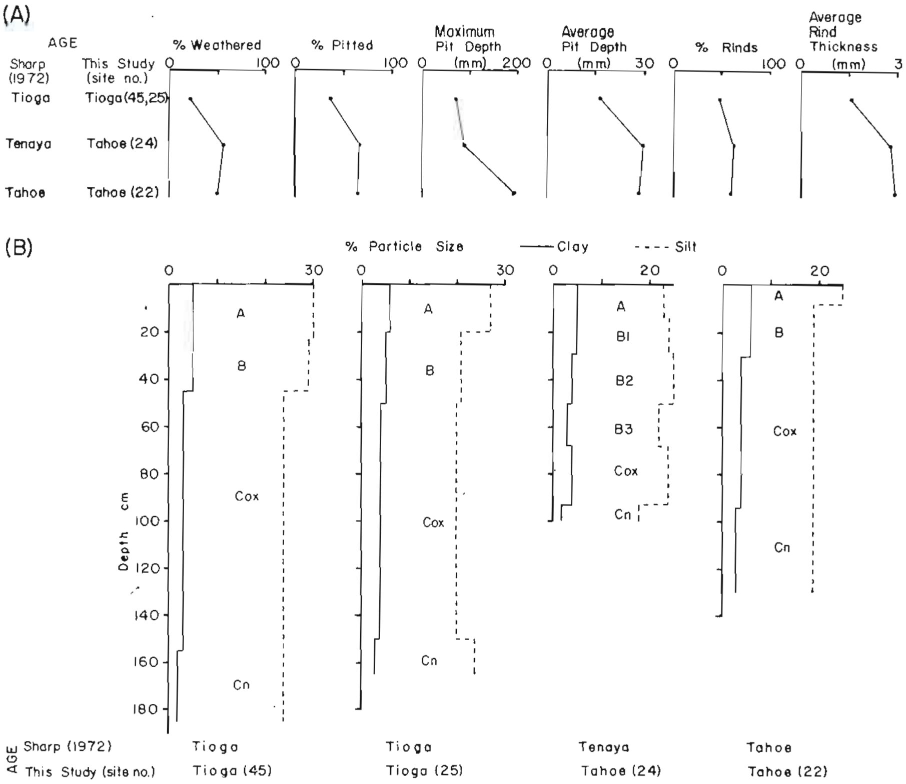

FIG. 11. (A) Selected RD and (B) soil data for deposits along Green Creek. Complete data and actual numbers are given in Tables 3 and 4.

files (Fig. 11b and Table 4). There is slight, if any, pedogenic clay buildup within the profiles. Subsurface grusification is minimal and similar between both sites (Fig. 12). Therefore, our data support Sharp's (1972) Tioga age assignment to this set of multiple moraines.

Tahoe Glaciation

Data collection sites were established along the crest of the major right lateral Tahoe moraine (site 22), and along two right lateral Tenaya moraine crests near site 24 (Fig. 10). The Tahoe and Tenaya moraines along Green Creek have similar morphology and weathering characteristics (Fig. 11a and Table 3). These moraines are substantially more weathered than the adjacent Tioga deposits and the RD data are comparable to those for Tahoe moraines in other drainages.

Data on the soil profiles of sites 24 (Sharp's Tenaya) and 22 (Sharp's Tahoe) show little variance from the post-Tioga soils (Fig. 11b and Table 4). The oxidation of these soils is not substantially redder nor deeper than that of post-Tioga soils (Table 4). In contrast, the depth of oxidation was used by Sharp (1972) to help differentiate Tioga and Tahoe Till, but part of this variation could be that his Tahoe Till site seems to be on a slope (Sharp, 1972, Fig. 6). Soil profiles on both Tenaya and Tahoe moraines show intense grusification and oxidation of granitic boulders which are very similar to Tahoe deposits in other valleys, and very much different from that in post-Tioga soils (Fig. 12).

Discussion

Data collected by Dickinson's group (1968) and Sharp (1972) appear to suggest that the Tahoe and younger glacial deposits along Green Creek record three separate glaciations. In contrast, our data suggest that this sequence records only two glacia-

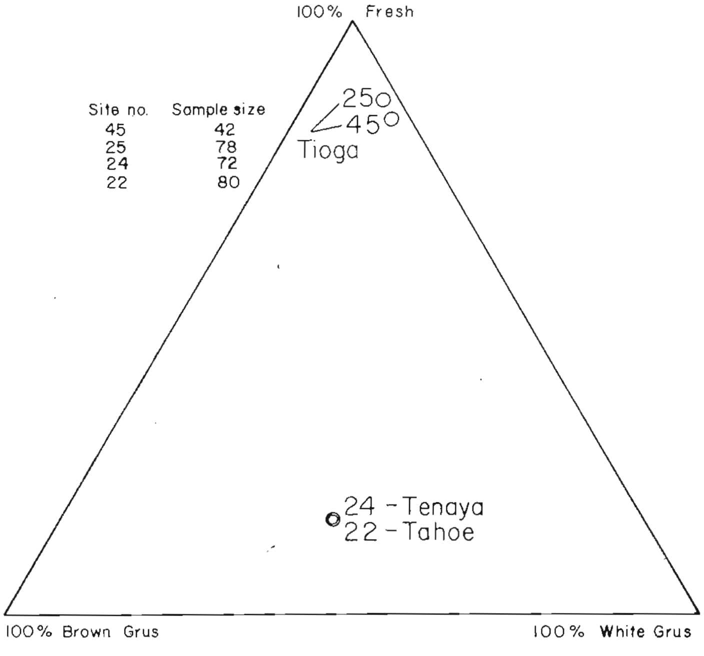

FIG. 12. Plot of fresh:white grusified:brown grusified subsurface granitic clasts exposed in roadcuts in moraines along Green Creek. Brown grus relates to stones that are both grusified and oxidized, whereas white grus relates to stones that are grusified but not markedly oxidized. Brown grusification denotes a greater amount or intensity of weathering. The names shown are those of Sharp (1972), and the site numbers are those of this study.

tions and that the Tenaya deposits of previous workers can reasonably be considered a product of the Tahoe Glaciation (Fig. 10). We do not know how to solve this dilemma of two vs three glaciations at the present time. It essentially comes down to comparing the different RD methods used; that is, whether or not increasing the number of sample sites of a few RD parameters is to be preferred over getting data on more parameters, including that for the subsurface, at fewer sites.

REGIONAL CRITERIA FOR FORMALLY NAMING GLACIATIONS

From the work in the four study areas we recognize that the limited sensitivity of RD techniques only allows a delineation of first-order glaciations, and that these in all likelihood will not delineate units of stadial rank (Porter, 1971). For example, RD data can suggest an indistinguishable closeness in the ages of moraines which by cross-cutting or nested relationships obviously represent pulsations of the ice front. Whereas some might argue that each pulsation is a glaciation or a stade, and give it a formal name, we contend that the main use of names is for subdivision of deposits that can be consistently recognized and distinguished from other deposits by the same and/or other workers. Thus, RD data presently provide acceptable data upon which mapping can be carried on from valley to valley using a formal stratigraphic nomenclature. In contrast to providing formal names for first-order events, second-order events can be informally designated as older or younger, or outer and inner, and used in local sequences, which in time may or may not be shown to correlate from valley to valley.

The question still remains, however, as to which RD data best define a mapping unit, and how much of a difference is expected before assigning deposits to different glaciations. The most consistent RD

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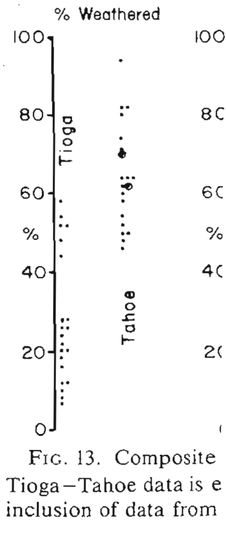

FIG. 13. Composite
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TABLE 6

Correlation of Glacial Deposits in Four Valleys, Eastern Sierra Nevada

Sawmill Canyon (S) (Dalrymple, 1964)	Mammoth Creek (Curry, 1971)	Sawmill Canyon (N)— Bloody Canyon (Sharp and Birman, 1963)	Green Creek (Sharp, 1972)	This Paper
Tioga	Tioga	Tioga	Tioga	Tioga
Tenaya	Tenaya	Tenaya	Tenaya	Tahoe
Tahoe	Tahoe	Tahoe	Tahoe	
Pre-Tahoe	Mono Basin	Mono Basin	Mono Basin	
	Casa Diablo			

data are weathering, pitting, rind development, and subsurface weathering. For different age assignments we at least expect to combine major variations in the conditions of subsurface granitic boulders with major variations in some surface weathering feature. If, however, soil development and subsurface grusification both suggest an age different from surface weathering, we favor the subsurface data and look for an explanation for the anomalous surface data. The magnitude of change needed in surface data to recognize separate glaciations is a doubling of at least some data. Finally, we suggest that only two first-order post-Sherwin Pleistocene glaciations can be demonstrated in the four valleys studied. These are here correlated with the Tahoe and Tioga Glaciations (Table 6).

Tioga vs Tahoe Deposits

Obvious morphological differences which exist between Tioga and Tahoe are that Tioga moraines are commonly less massive but more completely preserved than Tahoe moraines (Fig. 6). Along the moraine crest (Fig. 13), the percent of weathered granitic boulders in Tioga deposits is generally less than 30% compared to about 50% or more in Tahoe moraines. In no valley does the percent pitted boulders exceed 50% on Tioga moraines, but seldom is it less than 50% on Tahoe moraines. Pitting is fairly subtle on Tioga moraines, but results in grotesque boulder forms on Tahoe deposits (Fig. 14); in addition, maximum Tioga pit depths are considerably less than those of Tahoe age. Where average pit depth was measured (Sawmill Can-

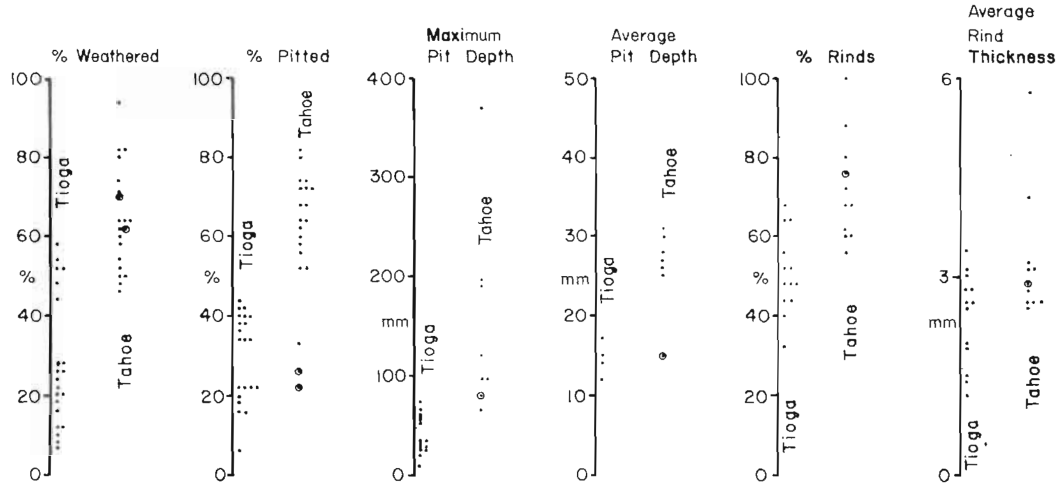

Fig. 13. Composite of the best surface RD data from the four valleys. Data are given in Table 3. The overlap in Tioga–Tahoe data is either unexplained, due to the overlap in data for Mammoth Creek drainage, or due to the inclusion of data from forested (⊙) Tahoe sites.

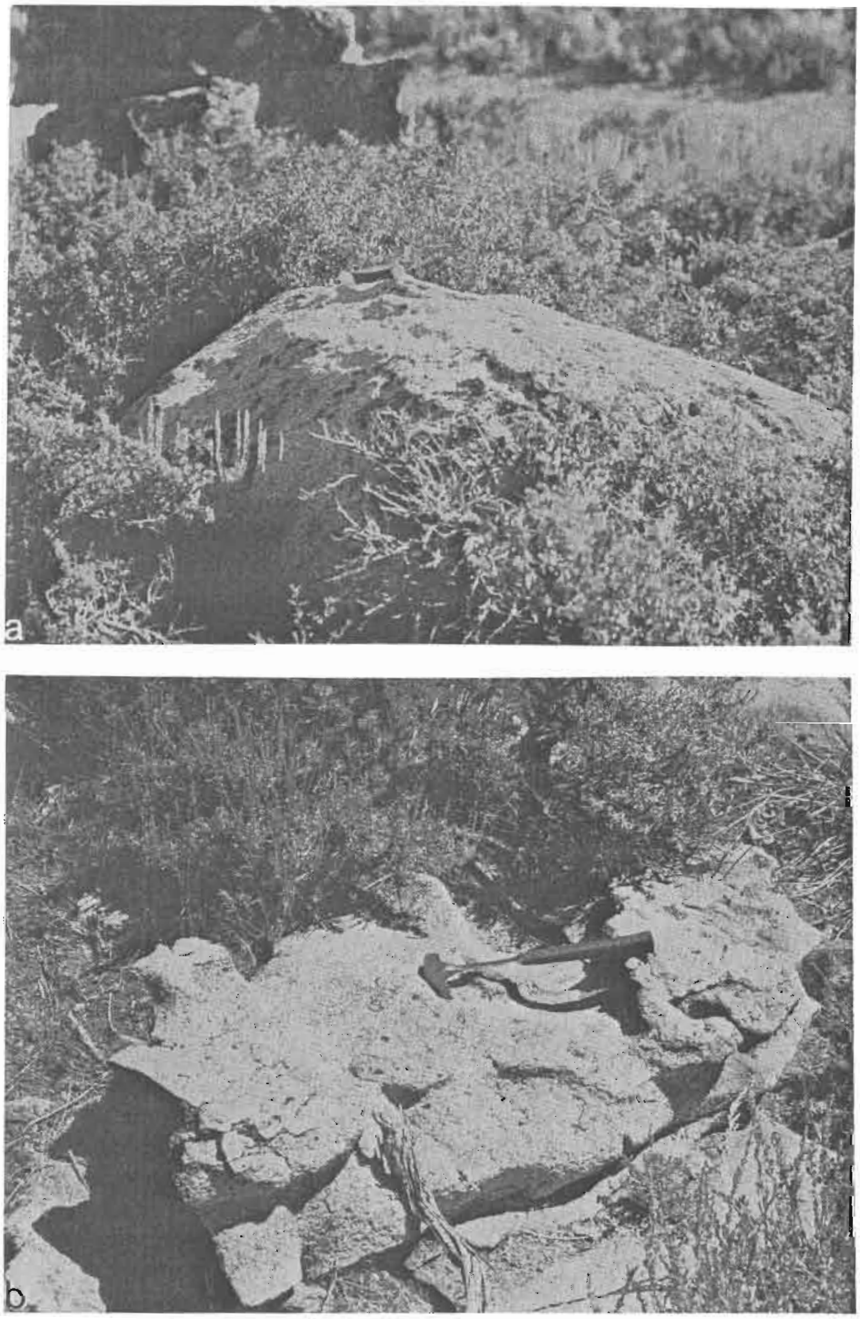

Fig. 14. Typical appearance of surface granitic boulders on (a) Tioga and (b) Tahoe moraines. The Tioga example is from site 20, Mammoth Creek, and the Tahoe example is from site 41, Sawmill Canyon (N)—Bloody Canyon.

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yon (N)—Bloody Canyon and Green Creek) it supports the Tioga and Tahoe age designation based on other data. The percent of boulders with weathering rinds and the average rind thickness work well for subdivision within a drainage, but overall comparisons of absolute numbers are less useful. Mafic inclusions in the granitic clasts on Tioga moraines are generally weathered in relief to less than 50 mm, whereas a relief in excess of 100 mm is common for boulders on Tahoe moraines. Other surface RD parameters are not consistently useful in separating the two units.

It is worth stressing that when surface RD data from the four valleys are grouped together (Fig. 13), there is an expected overlap in the values. The important thing, however, is to compare values in a single valley. If overlap in some data persists, one has to judge which could give an erroneous age, given the environment. If too many surface RD data conflict in age assignment, as at Mammoth Creek, subsurface RD data have to be considered before age assignment is attempted.

Subsurface data also are diagnostic in subdividing the Tioga and Tahoe deposits. The most consistent criterion is the weathered condition of the granitic clasts, for those in post-Tioga soils generally are fresh whereas those in post-Tahoe soils are generally grusified and oxidized to some extent (Fig. 15). In contrast, few of the soil-profile descriptions support the age difference between the Tioga and Tahoe deposits (Table 6). Oxidation is slightly more intense in some post-Tahoe soils than in post-Tioga soils. Most profiles of both ages display a slight clay increase toward the surface that could result from a combination of primary mineral weathering and downward translocation of eolian fines; it is doubtful a pattern that is so consistent can be solely due to parent material variations. Bt horizon development did help in discriminating the Casa Diablo Till from the younger tills in Mammoth Creek. If the tentative correlation of Casa Diablo deposits with Tahoe deposits is correct, the implied rate of development of the textural B horizon in this soil is matched only by that of a buried probable post-Tahoe soil in the eastern Carson Range along the Reno–North Lake Tahoe road (illustrated in Birkeland, 1974, Fig. 8-10). Soil clay mineralogy has previously been shown to be an ineffective tool for stratigraphic age assignment of many of these deposits (Birkeland and Janda, 1971).

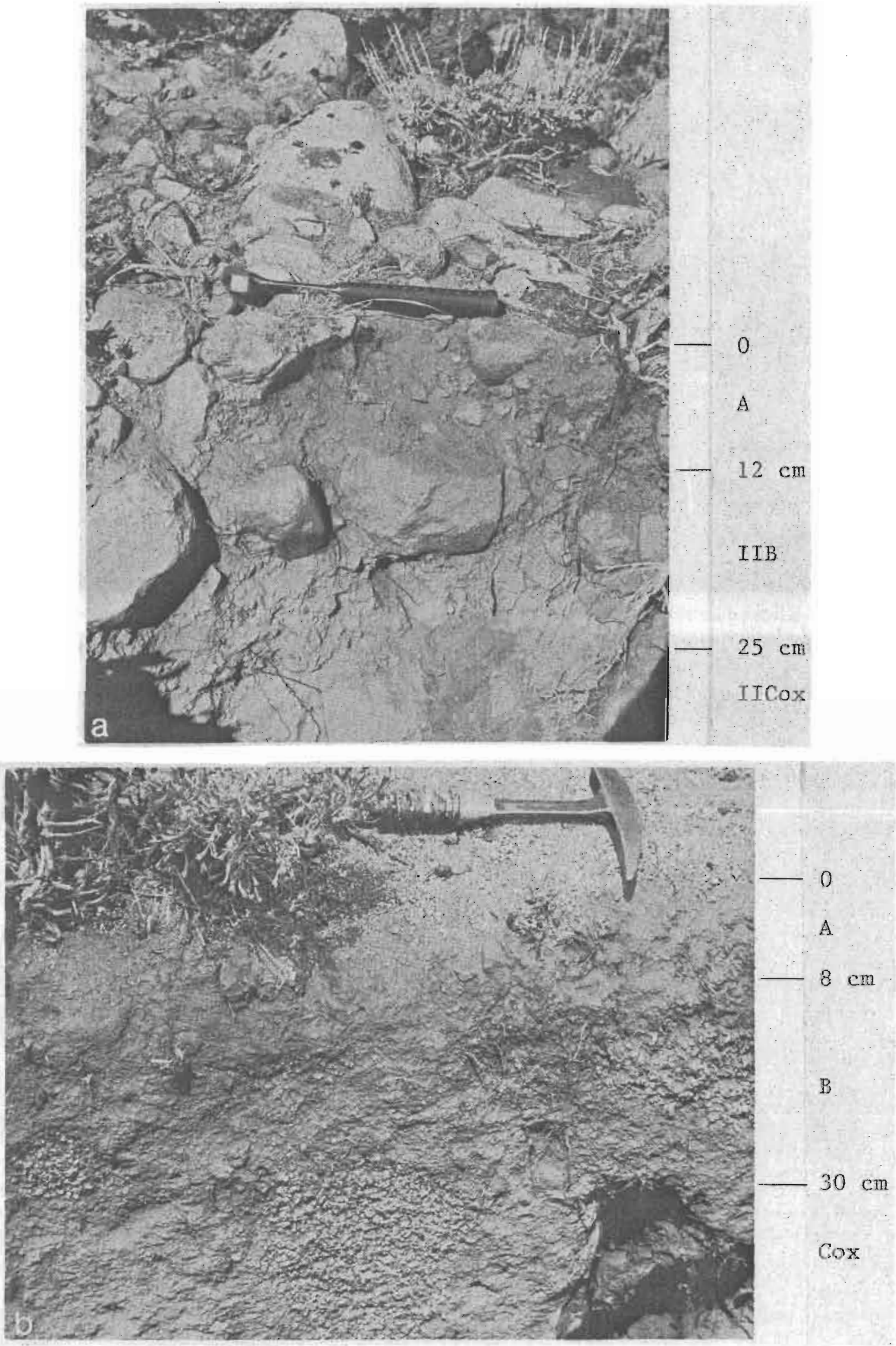
The Problem of the Tenaya and Mono Basin

Before this study, considerable debate has focused on the question as to where the Tenaya Glaciation of Sharp and Birman (1963) best fits in the glacial sequence of the eastern Sierra Nevada. The data of Sharp and Birman (1963), Birman (1964), Sharp (1969, 1972) and Dickinson's (1968) group show the Tenaya to be separable from both the Tioga and the Tahoe. On less data than those presented by the above workers, others have suggested that deposits of the Tenaya should be considered as an early advance of the Tioga Glaciation (Morrison, 1965; Smith, 1968; Birkeland and Janda, 1971). Our data here indicate that in at least three drainages the Tenaya is not readily separated from the Tioga, whereas in a fourth it is not separable from the Tahoe. Our suggestion is to drop the Tenaya as a first-order glaciation until further work is done.

The Mono Basin Glaciation of Sharp and Birman (1963) presents a similar problem in that Mono Basin Till has been shown to be quite similar to Tahoe Till at the Mono Basin type locality, if both are compared under sagebrush vegetation. Furthermore, the weathering characteristics of both deposits are similar to the deposit that both Sharp (1972) and we agree is Tahoe in the Green Creek drainage. Our tentative suggestion is to not use the Mono Basin terminology until more localities have been restudied.

CONCLUSION

E. Blackwelder, R. P. Sharp, and J. H. Birman have made very important con-



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tributions not only to the Sierra Nevada glacial sequence, but also to the development of RD techniques for dating deposits where absolute dating methods do not apply. We view our work here only as a further step in the refinement of both aspects of the work pioneered by them. Indeed, the reason this area was picked as one in which to refine RD techniques was because of their previous high-quality work in the area. We feel we have demonstrated a refinement in the techniques, with the by-product being that we offer an alternative to some of the age assignments for the deposits. This multiparameter approach to relative dating suggests that only two major groups of post-Sherwin pre-neoglacial tills, here grouped into the Tioga and Tahoe Glaciations, can be mapped. Deposits previously mapped as Tenaya seem best grouped with the Tioga in some drainages, but with the Tahoe in at least one drainage. Hence, we do not know how to define the Tenaya on RD data. In Sawmill Canyon (S) and Mammoth Creek, our outermost Tioga deposit is slightly more weathered than other Tioga deposits and could be the Tenaya of other workers. The type Mono Basin Till clearly was deposited prior to the major Tahoe moraine of the Sawmill Canyon (N)—Bloody Canyon area; however, under similar vegetation conditions, the data suggest no great age difference between the two deposits, and so we lump both into the Tahoe Glaciation. The type Casa Diablo Till has characteristics not unlike the Tahoe deposits of other valleys and so it also is tentatively correlated with the Tahoe Glaciation. We therefore suggest mapping only multiple Tioga and Tahoe deposits until better criteria for further subdivision are developed.

Problems remain in the use of RD methods, such as the necessary differences in data to justify different age assignments, operator variance, and how RD features are preserved and used for age indication in spite of erosional alteration of the landform. Because of this, we restate our contention (Birkeland *et al.* 1976) that the answers to questions brought up lie in the field, and any worker seriously considering a correlation with the east-central Sierra Nevada should visit the key sites in the field.

ACKNOWLEDGMENTS

We wish to thank J. P. Whipple for his capable field assistance. The comments of R. R. Curry, G. B. Dalrymple, and R. P. Sharp concerning their previous work are most appreciated. This study has benefited from our discussions over the years with R. A. Bailey, M. M. Clark, S. M. Colman, D. R. Crandell, R. R. Curry, R. J. Janda, K. L. Pierce, R. P. Sharp, and C. Wahrhaftig. We appreciate the constructive criticisms of Janda, Pierce, and Sharp on the manuscript in its various stages. The conclusions are our own and none of the above are necessarily in agreement with them. We also wish to thank Mr. Rolf Kihl of INSTAAR, University of Colorado, for much of the laboratory data. This work was supported by USGS Grant No. 14-08-0001-G-202.

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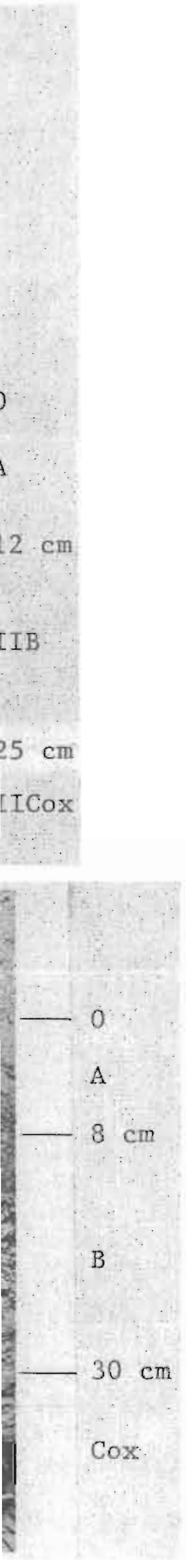

FIG. 15. Typical (a) post-Tioga and (b) post-Tahoe soils. Note that in (a) the subsurface granitic boulders are fresh whereas in (b) they are grusified. The post-Tioga soil is developed at site 42, Sawmill Canyon (N)—Bloody Canyon, and the post-Tahoe soil at site 22, Green Creek.

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