# Geologic Map of the Willows 1:100,000 Quadrangle, California

by

M. C. Blake[1], Jr., E. J. Helley[1],

A. S. Jayko[1], D. L. Jones[2], and H. N. Ohlin[3]

Open-File Report 92-271



[1]U.S. Geological Survey-MS 975
345 Middlefield Road
Menlo Park, CA 94025

[2]Department of Geology
University of California
Berkeley, CA 94720

[3]908 Evans Avenue
Reno, NV 89512

1992

# GEOLOGIC MAP OF THE WILLOWS 1:100,000 QUADRANGLE, CALIFORNIA

by

M. C. Blake, Jr., E. J. Helley,

A. S. Jayko, D. L. Jones, and H. N. Ohlin

## INTRODUCTION

The Coast Ranges in the Willows quadrangle consist of deformed and metamorphosed rocks of the Franciscan Complex and contain rocks that range in age from Middle Jurassic to Cretaceous. The Great Valley province includes a thick apron of moderately deformed Late Jurassic and Cretaceous marine strata that contain detritus derived from uplifted basement rocks of the Klamath Mountains and the Sierra Nevada to the north and east of the mapped area (Fig. 1). In the western foothills of the Sacramento Valley, these strata rest on the Coast Range ophiolite. In the central part of the Sacramento Valley, a mantle of Tertiary and Quaternary detrital continental deposits overlies the Great Valley sequence and grades eastward into coeval volcanic material derived from the Cascade Range province. The stratigraphic and structural relations shown on the map provide a key to understanding how the rocks of these various provinces were formed and subsequently assembled.

For the compilation of this geologic map, Blake, Jayko, Jones, and Ohlin are responsible for the pre-Cenozoic rocks of the Coast Ranges and Great Valley provinces and Helley for the late Cenozoic deposits of the Sacramento Valley province.

# GEOLOGY

## Sacramento Valley and Western Foothills Province

East of the Franciscan Complex and the slices of Galice (?) Formation, is the Elder Creek terrane (Blake and others, 1985), that consists of the basal Round Mountain serpentinite melange structurally overlain by the Coast Range ophiolite that is, in turn, depositionally overlain by the Great Valley sequence. The Round Mountain melange consists of sheared and serpentinized harzburgite and dunite containing blocks and slabs of radiolarian chert, basalt, diabase, and gabbro. These blocks and slabs are remnants of a once coherent terrane that lay between the Franciscan Complex and the overlying Coast Range ophiolite. Based on their subalkaline geochemistry, they were considered to be part of the Franciscan Complex (Shervais and Kimbrough, 1985), however, they lack any penetrative deformation or high P/T metamorphic minerals that characterize the Franciscan rocks to the west. Also present are a few blocks of amphibolite, and garnet amphibolite. Hornblende from one of these blocks along Thomes Creek was dated at 162± Ma (Warren Sharp, personal communication, 1992), and probably represents remnants of a high P/T metamorphic sole that apparently form during obduction of hot ophiolite onto continental margins (Coleman, 1977).

The Coast Range ophiolite structurally overlies the melange along the Beehive Flat detachment fault (Jayko and others, 1987). Although dismembered by several generations of faults, it contains all of the elements of an ophiolite sequence. The lower part is best preserved along the northwest-trending ridge west of Red Mountain, where layered ultramafic rocks (wehrlite, dunite, clinopyroxenite) grade into layered gabbro that, in turn, is overlain by intrusive gabbro plus minor plagiogranite. The upper part is best preserved in the canyon of Digger Creek, east of the Beehive Flat fault. Here, and in a few other places, intrusive gabbro is overlain by a sheeted dike complex that, in turn, is overlain by basalt. Locally, especially in the area east of Brush Mountain, the basaltic volcanic rocks appear to be intruded by more siliceous volcanic rocks and probably by diorite and quartz diorite. These instrusive rocks also occur as small (1-5 m) dikes cutting harzburgite, dunite, and layered ultramafics. One of these dikes along the South Fork of Elder Creek was dated at 155 Ma (Lanphere, 1971). Hornblende from intrusive gabbro at Eagle Peak was dated at 166 Ma (McDowell and others, 1984) and zircon from plagiogranite near Beehive Flat gave a U-Pb age of 169 Ma (Jason Saleeby, written commun., 1989). It thus appears that the igneous rocks of the Coast Range ophiolite probably formed during two distinct periods in the Jurassic.

The Crowfoot Point ophiolitic breccia marks the top of the ophiolite in this area. Along the South Fork of Elder Creek, where it was first discovered, it is about 60 meters thick and consists largely of angular to subrounded clasts (0.1-1.0 m) of basalt, diabase, plagiogranite, gabbro, and pyroxenite. A large (10 m) slab of pillow breccia occurs near the top of the unit. Farther south, near Crowfoot Point, the clasts are much larger, including lenses of radiolarian chert up to 7 m. The breccia lies in depositional contact on many different ophiolite units indicating that widespread faulting was taking place during its deposition. The sedimentology of the breccia has been studied in detail by Robertson (1990) who concluded that the breccia formed during extensional faulting of the ophiolite probably in a fore-arc setting above a subduction zone.

The Great Valley sequence is the sedimentary cover to the ophiolite in this area. At the base, along the South Fork of Elder Creek, the angular clasts in the upper part of the ophiolitic breccia grade in less than a meter into mudstone containing small pebbles of ophiolite. A similar contact near Crowfoot Point yielded several specimens of *Buchia rugosa* of late Jurassic (Kimmeridgian?) age (Jones, 1975). Above this are thousands of meters of mudstone plus subordinate sandstone and conglomerate of Upper Jurassic, Lower Cretaceous, and Upper Cretaceous age (Jones and Imlay, 1969). On the map we have shown most of the sedimentary rocks of the Great Valley sequence as part of the Elder Creek terrane. This is based on the fact that in the Red Bluff quadrangle (Blake and others, 1984) there are two different Great Valley sequences, one deposited on the Coast Range ophiolite and the other on Sierran/Klamath basement. These two sequences are separated by the Cold Fork fault zone. Within the Willows quadrangle, we have no exposed Sierran-Klamath basement and can only guess that such basement extends westward beneath the eastern part of the quadrangle at least as far as the Orland Buttes. We show these Cretaceous rocks of the Great Valley sequence as Kms rather than ecms, implying that they are underlain by Sierran basement. This is further discussed in the section dealing with regional structure.

The eastern two-thirds of the Willows quadrangle contains low-rolling topography that slopes toward the Sacramento River, the largest drainage system in northern California. This part of the map is underlain by late Cenozoic sedimentary and volcanic rocks that rest with marked unconformity on Upper Cretaceous rocks of the Great Valley sequence.

The western part of the Cenozoic cover consists of Pliocene continental deposits of the Tehama Formation. The Nomlaki Tuff member of the Tehama and Tuscan Formations, which occurs locally at or near the base of both formations, blanketed much of the northern Sacramento Valley about 3.4 m.y. ago; approximately the time of major Neogene uplift and erosion of the Coast Ranges province. Continental deposits of the Tehama Formation accumulated as coalescing alluvial fans along the eastern margin of the rising Coast Ranges. East of the map area, lahars and minor lava flows, composed of basalt and basaltic andesite, flowed westward from several volcanic centers near Lassen Peak at the southern end of the Cascade Range forming the Tuscan Formation. Rocks of the Tehama and Tuscan Formations interfinger in a zone several kilometers wide near the present channel of the Sacramento River, which we have taken arbitrarily as the formational boundary.

The Tehama and Tuscan Formations are beveled and capped by the Red Bluff Formation, a thin unit of bright-red gravel with a red sandy matrix. The Red Bluff Formation generally forms the highest part of the valley landscape on the west side of the Sacramento River, where it occurs as remnants of a highly dissected and eroded geomorphic surface (Helley and Jaworowski, 1985). We interpret the Red Bluff Formation as a sedimentary cover on a pediment surface because: 1) the Red Bluff was apparently deposited on a cut surface of low relief that extends regionally across various older rock types, 2) the deposits are thin and locally derived, and 3) the coarse, poorly sorted gravel was deposited by a very different flow regime than the one that deposited the underlying fine-grained sediment of the Tehama Formation. The pediment and the Red Bluff gravels apparently formed during a period of lateral planation by high-gradient streams when impeded drainage on the Sacramento River raised local base level. Well-developed, non-calcic, brown soils (Xeralfs) of the Redding and Corning Soil Series characterize the Red Bluff Formation.

On the west side of the Sacramento Valley, all units younger than the Red Bluff occur in nested terraces usually tens of meters below the pediment surface. This depositional scheme is partially developed on the east side of the valley, but, locally, younger alluvial deposits and volcanic rocks extend over the Red Bluff surface (Harwood and others, 1981). Four Pleistocene terrace deposits have been recognized on the west side of the Sacramento Valley and have been correlated by absolute ages, soil profile development, geomorphic expression, and superposition with the Riverbank and Modesto Formations of the San Joaquin Valley (Marchand and Allwardt, 1981). The Riverbank and Modesto Formations are divided into informal upper and lower members. Original alluvial materials on the terraces on the west side of the valley are virtually identical lithologically but each deposit has a characteristic elevation, degree of dissection, and soil-profile development that are chiefly a function of age. Terrace deposits on the east side of the Sacramento Valley are lithologically indistinguishable from each other, but their volcanic debris readily distinguishes them from deposits on the west side of the valley. Correlation of east-side terrace deposits is based on the same criteria used to separate the west-side terrace deposits. The greatest elevation difference within the Pleistocene deposits exists between the top of the Red Bluff Formation and the highest terrace of the Riverbank Formation, the oldest Pleistocene terrace. Streams throughout the Sacramento Valley incised their valleys tens of meters between deposition of the Red Bluff and the deposition of the lower member of the Riverbank, which suggests a major, regional lowering of base level. The difference in elevation of terraces of the lower and upper Riverbank and the lower and upper Modesto terraces, however, is only a few meters. Terrace deposits of Riverbank age are well developed and best preserved along Thomes Creek and Stony Creek.

Deposits of Modesto age are best preserved in the same areas as those of Riverbank age. Clearly, the Riverbank and Modesto deposits were laid down by the same water courses that exist today. The volume of Holocene deposits accumulating at present in open non-vegetated sediment-filled channels along the Sacramento River and its tributaries commonly is significantly smaller than the volume of material in the Modesto, Riverbank, and the older deposits.

## Coast Ranges Province

The Franciscan rocks of the northern Coast Ranges have been divided into three belts and most of these belts have been divided further into terranes (Blake and others, 1985).

### Central Franciscan Belt

The Central Franciscan belt is found in the south part of the Willows quadrangle. It consists of an argillite-matrix melange and contains numerous blocks and slabs of oceanic basalt and chert, rare pelagic limestone, metamorphic rocks (blueschist, eclogite, and amphibolite) plus slabs of previously accreted Eastern Franciscan belt rocks, Coast Range ophiolite, and Great Valley sequence. Earlier, it was believed that these latter rocks were all klippen related to thrust faulting but structural studies in the adjacent Covelo quadrangle (Jayko and others, 1989) indicate that many of the fault slices seen in the Central Franciscan belt were transported northward during two episodes of strike-slip faulting. Structures in the Willows quadrangle suggest that the northwest-trending high-angle faults, bounding the various Central Franciscan belt units, have been overridden by the Eastern Franciscan belt along the Estell Creek thrust and that a window of Central belt rocks is present along Estell Creek. The significance of these structural relationships will be further discussed in the section dealing with tectonic history.

## Eastern Franciscan Belt

The Eastern Franciscan belt contains two terranes. The structurally lower Yolla Bolly terrane has been subdivided into several informal thrust-bound units based on differences in lithology and metamorphic grade. All of the graywackes, however, have at least a weakly developed cleavage (TZ-2A Jayko and Blake, 1985) and contain lawsonite and albite. The structurally highest unit is the Taliaferro Metamorphic Complex (Suppe, 1973). It consists of jadeite-bearing metagraywacke, textural zone 2B (TZ-2B) (Jayko and Blake, 1989), metachert, and metavolcanic rocks, the latter two containing distinctive blue amphibole. The Chicago Rock melange varies from relatively coherent broken formation to rather chaotic melange, containing abundant blocks of greenstone and chert as well as rare knockers of blueschist and sparse intrusive serpentinite. The upper contact with the Valentine Spring Formation is, in most places, the Sulphur Creek thrust fault but, locally, a tectonic slice of Taliaferro Metamorphic Complex is present between these two units. The metagraywacke of Hammerhorn Ridge consists of coherent graywacke and chert plus minor intrusive diabase-gabbro. The upper contact is placed at the top of the coherent sequence and is inferred to be a thrust fault (Chicago Camp thrust) although the thrust movement was probably distributed throughout the overlying Chicago Rock melange. Three other Yolla Bolly units are present as slabs within the Central Franciscan belt along the western margin of the Willows quadrangle. One of these (ybu) is a graywacke unit that could be either Hammerhorn Ridge or Chicago Rock. The Hull Mountain unit greatly resembles the metagraywacke of Hammerhorn Ridge but contains fossils of Middle Cretaceous (Cenomanian) age. The Sanhedrin Mountain unit is found in the extreme southwest corner of the quadrangle, separated from the Hull Mountain unit by the active Bartlett Springs fault zone (DePolo and Ohlin, 1984). To the west, in the Covelo quadrangle, these rocks include much radiolarian chert and closely resemble the Hammerhorn Mountain unit also.

The Pickett Peak terrane contains two distinctive units, the South Fork Mountain Schist, largely quartz-mica schist derived from mudstone, and the Valentine Spring Formation, largely metagraywacke. Both locally contain basal metabasalt and, in places, a thin (1-2 m thick layer of metachert occurs above the metabasalt and below the clastic meta-sedimentary rocks.

The rocks of the Pickett Peak and Yolla Bolly terranes were formerly thought to have been metamorphosed during the same Cretaceous event (Blake and others, 1967). However, recent work ( Worrall, 1981; Jayko and others, 1986; Jayko and Blake, 1989) indicates that: 1) a progressive eastward increase in textural and metamorphic grade occurs in each terrane, 2) rocks of the Pickett Peak terrane contain early deformational-metamorphic structures not seen in the rocks of the Yolla Bolly terrane, and 3) a major thrust fault separates the two terranes (Sulphur Creek fault of Worrall, 1981). Although the exact timing of the two metamorphic events is not clear, the regional geologic relationships and available radiometric and fossil data suggest that both events occurred during the Cretaceous.

The eastern boundary of the Franciscan Complex is the Coast Range fault (Jayko and others, 1987). Along this fault, in several places, are thin slivers of metagraywacke and slate plus metavolcanic rocks that have been correlated with the Galice Formation of the Smith River subterrane of the Klamath Mountains (Jayko and Blake, 1986).

## REGIONAL STRUCTURE

The Willows quadrangle is transected by a major north-trending fault, earlier named the Coast Range thrust (Bailey and others, 1970). Subsequent studies (Hopson and others, 1981; Worrall, 1981; Jayko, 1983) pointed out that this is probably a Cenozoic high-angle fault and better called the Coast Range fault (Jayko and others, 1987). Within most of the mapped area, the fault usually appears to dip steeply to the east suggesting a normal sense of movement. Locally, however, it dips steeply west with a reverse sense of offset (Earth Science Associates, 1980). Earthquake swarms of magnitude 1, 2, and 3 (focal mechanism not reported), located along the Coast Range fault in the vicinity of Thomes Creek, suggest that the fault may be active (Calif. Dept. Water Resources, unpublished data).

Within the Pickett Peak terrane, there are at least three low-angle thrust faults. The structurally highest Tomhead fault was first described by Worrall (1981) from an area to the north. There, the fault was defined on the basis of differences in metabasalts above and below the thrust, by the presence of metachert with the metabasalt above the fault, by the composition of mica schist above and below the fault, and by contrasts in fabric on opposite sides of the fault. We have not seen the Tomhead fault in the Willows quadrangle but, for the same reasons given by Worrall, we suspect that it separates the large areas of north-trending metabasalt in the northeast portion of the terrane from those to the west and south. The fault that separates the South Fork Mountain Schist from the underlying Valentine Spring Formation has been named the Ball Mountain fault after a prominent peak that the fault crosses to the west (Jayko and Blake, 1989). Because this fault places more metamorphosed rock on less metamorphosed rock, it is thought to be a thrust fault. Another thrust fault is found in the extreme northwest corner of the area. It occurs within the Valentine Spring Formation and places TZ-3A metagraywacke on TZ-2B metagraywacke. This thrust is correlated with the Log Springs fault to the south (Suppe, 1973). The age of movement on these thrusts is poorly constrained but it clearly postdates blueschist-facies metamorphism dated at about 125 Ma (Lanphere and others, 1978; McDowell and others, 1984).

Within the Elder Creek terrane there are several generations of faults. The most prominent structure is the Beehive Flat detachment fault that separates the ophiolite from underlying serpentine melange. This is believed to be a low-angle normal fault active in latest Cretaceous and/or early Cenozoic time (Jayko and others, 1987) because it places higher levels of the ophiolite down onto lower levels (e.g. diabase down onto serpentinized peridotite) and because section is omitted along it. Within the ophiolite there are numerous high-angle faults separating different ophiolitic units. Most of these appear to be normal faults with higher ophiolite units (e.g. basalt) faulted down against lower units (e.g. gabbro). The mapped relations indicate at least two periods of normal faulting, the earliest of which predates deposition of the ophiolitic breccia. Most of the normal faults, however, affect the ophiolitic breccia and some offset the sedimentary rocks of the Great Valley sequence.

Superposed on the normal faults is a complex, northwest-trending zone of left-lateral strike-slip faults. These, in the north, are part of the Paskenta fault zone (Jones and Irwin, 1971) while to the south, we have mapped the Digger Creek, Mill Creek, and Slate Creek faults. Also present, are several thrust faults that place serpentine melange on top of the Great Valley sequence. Recent structural mapping along the South Fork of Elder Creek (Glen, 1990) suggests that the Paskenta and related fault zones are tear faults with left-lateral movement being synchronous with west-directed thrusting. The possible relationship of these structures to deeper thrust faulting and eastward tectonic wedging is discussed by Wentworth and others, 1984; Glen, 1990; and Unruh and others, 1991. In the Willows quadrangle, this tectonic wedging is manifested by both east- and west-directed thrusting within the ophiolitic rocks and along the Stony Creek fault, which places serpentine melange on Great Valley sequence. In addition, the Fruto syncline and Sites anticline along the southern part of the quadrangle are believed to lie above a "blind" thrust that moved the rocks of the Elder Creek terrane eastward over the Great Valley sequence, which was deposited on Sierran basement. Support for this hypothesis is seen in seismic reflection line S-51, the eastern part of which is shown on Figure 5 of Wentworth and others, 1984. This line ends just east of the Sites anticline and shows that the top of the easternmost wedge of Great Valley sequence, presumably part of the Elder Creek terrane, has been driven eastward onto Sierran basement, peeling up the overlying Great Valley sequence that was originally deposited on this basement. These data suggest that the "roof" thrust that forms the top of this easternmost wedge should surface just to the east of the Sites anticline. A through-going fault, named the Salt Lake fault by Brown and Rich (1961), was mapped in this position to the south in the Lodoga quadrangle. That fault has not been mapped in the Willows quadrangle and, instead, we show its projected location as a poorly-located, approximate boundary between the Elder Creek terrane and the Great Valley sequence.

In the Red Bluff quadrangle, we considered that stratal continuity between the two Great Valley sequences was established by Turonian time but the data presented here suggest that they are probably separated by a fault. The timing of this thrusting and wedging is not clear here, but subsurface geophysical data suggest that it may have begun in the Eocene (Unruh and others, 1991).

Pliocene and younger deposits in the Sacramento Valley and eastern foothills show evidence of deformation that occurred within the past 2.5 m.y. (Harwood, 1984; Helley and Jaworowski, 1985; Harwood and Helley, 1987) The north-trending Corning fault, which lies west of the Chico monocline, has no surface expression in the Sacramento Valley but is defined by seismic reflection data (Harwood, 1984; Harwood and Helley, 1987). Seismic reflection data indicate a moderately steep, eastward dip and reverse, east-side-up movement on the Corning fault. Upward and westward movement of the hanging wall of the fault deformed the Tehama and Red Bluff Formations into the north-trending North and South Corning domes (Helley and Jaworowski, 1985; Harwood and Helley, 1987). The Los Molinos syncline, which lies between the Corning fault and the Chico monocline, forms a north-northwest-trending trough that locally controls the position of the Sacramento River.

## TECTONIC SUMMARY

The Willows quadrangle contains four major tectonostratigraphic terranes: Pickett Peak, Yolla Bolly, Central Franciscan and Elder Creek. (Fig. 2). Small slivers of a fifth terrane, the Smith River subterrane of the Western Klamath terrane, occur along the Coast Range fault between the Franciscan Complex and the Elder Creek terrane. The Franciscan rocks are part of a late Mesozoic subduction complex that was active during the Cretaceous. The Elder Creek terrane consists of the Coast Range ophiolite and the Great Valley sequence that was deposited on the ophiolite. The Smith River subterrane of the Western Klamath terrane is probably an attenuated remnant of an island arc complex that was overthrust by the Coast Range ophiolite during the Nevadan orogeny (Jayko and Blake, 1986) After subduction of the Pickett Peak terrane, further accretion and subduction of the Yolla Bolly terrane resulted in uplift of the older subduction complex and extensional faulting of the upper plate rocks, Smith River subterrane of the western Klamath terrane and Elder Creek terrane. This probably occurred near the end of the Cretaceous. Following this extensional faulting, there was a return to oblique subduction and dispersal of attenuated fragments of Pickett Peak, Yolla Bolly, and Elder Creek terranes into the Central melange terrane. In addition, numerous blocks and slabs of oceanic basalt (greenstone) and radiolarian chert, high-grade blueschist and eclogite, and rare pelagic limestone, were introduced into the Central Franciscan terrane probably from the south. Later, probably beginning in the early Cenozoic, all of these rocks were imbricated by both westward and eastward-directed thrusting. This is seen in the thrusting along the Estell Creek thrust fault, within the Elder Creek terrane along the Stony Creek fault, and also by the northwest-trending tear faults (Paskenta fault, etc.) This latest event is believed to be a manifestation of the deeper, eastward-directed tectonic wedging that was described earlier, and is probably continuing today as part of San Andreas transpression.

ACKNOWLEDGMENTS

Numerous geologists helped in the field and in the preparation of this map and report. Special thanks go to Kea Umstattd who did the final drafting and worked on the Description of Map Units and Figures.

## REFERENCES LISTED

Bailey, E.H., Blake, M.C., Jr., and Jones, D.L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges, *in* Geological Survey research, 1970: *U.S. Geological Survey Professional Paper 700-C, p. C70-C81.*

Blake, M.C., Jr., Irwin, W.P., and Coleman, R.G., 1967, Upside-down metamorphic zonation, blueschist facies, along a regional thrust in California and Oregon: *U.S. Geological Survey Professional Paper 575C,* p. 1-9.

Blake, M.C., Jr., Harwood, D.S., Helley, E., Irwin, W.P., Jayko, A.S., and Jones, D.L., 1984, Preliminary geologic map of the Red Bluff 1:100,000 quadrangle: *U.S. Geological Survey Open-File Report 84-105.*

Blake, M.C., Jr., Jayko, A.S., and McLaughlin, R.J., 1985, Tectonostratigraphic terranes of Northern California: *in* Howell, D.G., ed., Tectonostratigraphic terranes of the Circumpacific region: Earth Science Series, v. 1, *Circumpacific Council for Energy and Mineral Resources,* p. 159-171.

Blake, M.C., Jr., Jayko, A.S., McLaughlin, R.J., and Underwood, M.B., 1988, Metamorphic and tectonic evolution of the Franciscan Complex, northern California, *in* W.G. Ernst, ed., *Metamorphism and crustal evolution of the western United States*, Rubey Vol. VII, Englewood Cliffs, NJ, Prentice-Hall, Inc., p. 1036-1059.

Brown, R.D., Jr., and Rich, E.I., 1961, Geologic map of the Lodoga quadrangle, Glenn and Colusa Counties, California: *U.S. Geological Survey Oil and Gas Investigations Map OM-210*, scale 1:48,000.

Coleman, R.G., 1977, Ophiolites, Springer, New York, 229 p.

Dalrymple, G.B., 1964, Cenozoic chronology of the Sierra Nevada, California: *University of California Publications Bulletin, Department of Geological Sciences,* v. 47, 41 p.

DePolo, C.M., and Ohlin, H.N., 1984, The Bartlett Springs Fault Zone: an eastern member of the California plate boundary system: *Geological Society of America, Abstracts with Programs*, v. 16, no. 6, p. 486.

DeWit, M.W., 1991, Glacial geology of the Yolla Bolly-Middle Eel Wilderness, northern California: *Geological Society of America, Abstracts with Programs*, v. 23, no. 2, p. 18.

Earth Sciences Associates, 1980, Seismic and fault activity study, proposed Glenn Reservoir Complex: unpublished report to California Department of Water Resources, by *Earth Sciences Associates*, Palo Alto, California, project no. 2086.

Evernden, J.F., Savage, D.E., Curtis, G.H., and James, G.T., 1964, Potassium-argon ages and the Cenozoic mammalian chronology of North America: *American Journal of Science*, v. 262, p. 145-198.

Ghent, E.D., 1964, Petrology and structure of the Black Butte area, Hull Mountain and Anthony Peak quadrangles northern Coast Ranges, California: Ph.D. thesis, University of California, Berkeley.

Glen, R.A., 1990, Deformation and thrusting in some Great Valley rocks near the Franciscan Complex, California, and implications for the tectonic wedging hypothesis: *Tectonics*, v. 10, p. 1451-1477.

Harwood, D.S., 1984, Evidence for late Cenozoic east-west compressive tectonism in the Sacramento Valley, California, *in* Crouch, J .K., and Bachman, S.B., eds., Tectonics and sedimentation along the California margin: *Society of Economic Paleontologists and Mineralogists, Pacific Section*, San Diego, Calif., 1984, v. 38, p. 87-100.

Harwood, D.S., and Helley, E.J., 1987, Late Cenozoic tectonism of the Sacramento Valley, California: *U.S. Geological Survey Professional Paper 1359*, 98 p.

Harwood, D.S., Helley, E.J., and Doukas, M.P., 1981, Geologic map of the Chico Monocline and northeastern part of the Sacramento Valley, California: *U.S. Geological Survey Miscellaneous Investigations Map I-1238*, scale 1:62,500.

Helley, E.J., and Harwood, D.S., 1985, Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California: *U.S. Geological Survey Miscellaneous Field Studies Map MF-1790*, scale 1:62,500.

Helley, E.J., and Jaworowski, Cheryl, 1985, The Red Bluff pediment, a datum plane for locating Quaternary structures in the Sacramento Valley, California: *U.S. Geological Survey Bulletin 1628*, 13 p.

Hopson, C. Mattinson, J.M., and Pessagno, E.A., Jr., 1981, Coast Range ophiolite, western California, *in* Ernst, W.G., ed., *The geotectonic development of California: Englewood Cliffs*, N. J., Prentice-Hall, p. 418-510.

Jayko, A.S., 1983, Deformation in low-grade blueschists of the Eastern Franciscan belt, northern California: *Geological Society of America Abstracts with Programs*, v. 15, no. 5, p. 313.

Jayko, A.S., 1984, Structure and deformation of the eastern Franciscan belt, northern California: Santa Cruz, California, University of California, Ph.D. thesis, 206 p.

Jayko, A.S., and Blake, M.C., Jr., 1986, Significance of Klamath rocks between the Franciscan Complex and Coast Range ophiolite, northern California: *Tectonics*, v. 5, no. 7, p. 1055-1071.

Jayko, A.S., and Blake, M.C., Jr., 1989, Deformation of the Eastern Franciscan belt, northern California: *Journal Structural Geology,* v. 11, 375-390.

Jayko, A.S., Blake, M.C., Jr., and Brothers, R.N., 1986, Blueschist metamorphism of the Eastern Franciscan belt, northern California, *in* Evans, B.W., and Brown, E.H., eds., Blueschists and Ecologites: *Geological Society of America, Memoir 164*, p. 107-123.

Jayko, A.S., Blake, M.C., Jr., and Harms, Tekla, 1987, Attenuation of the Coast Range ophiolite by extensional faulting and nature of the Coast Range "thrust," California: *Tectonics*, v. 6, p. 475-488.

Jayko, A.S., Blake, M.C., Jr., McLaughlin, R.J., Ohlin, H.N., Ellen, Steve, and Kelsey, Harvey, 1989, Reconnaissance geologic map of the Covelo 30 by 60 minute quadrangle, northern California: *U.S. Geological Survey Miscellaneous Field Studies Map MF-200*, scale 1:100,000.

Jones, D.L., 1975, Discovery of *Buchia Rugosa* of Kimmeridgian age from the base of the Great Valley sequence: *Geological Society of America Abstracts with Programs*, v. 7, no. 3, p. 330.

Jones, D.L., and Imlay, R.W., 1969, Structural and stratigraphic significance of the *Buchia* zones in the Colyear Springs-Paskenta area, California: *U.S. Geological Survey Professional Paper 647-A,* 24 p.

Jones, D.L., and Irwin, W.P., 1971, Structural implications of an offset Early Cretaceous shoreline in northern California: *Geological Society of America Bulletin*, v. 82, p. 815-822.

Lanphere, M.A., 1971, Age of the Mesozoic oceanic crust in the California Coast Ranges: *Geological Society of America Bulletin*, v. 82, p. 3209-3212.

Lanphere, M.A., Blake, M, Jr., and Irwin, W.P., 1978, Early Cretaceous metamorphic age of the South Fork Mountain Schist in the northern Coast Ranges of California: *American Journal of Science*, v. 278, no. 6, p. 798-815.

Lehman, D.H., 1974, Structure and petrology of the Hull Mountain area, northern California: Ph.D. thesis, University of Texas at Austin.

Marchand, D.E., and Allward, Alan, 1981, Late Cenozoic stratigraphic units, northeastern San Joaquin Valley, California: *U.S. Geological Survey Bulletin 1470*, 70 p.

McDowell, F.W., Lehman, D.H., Gucwa, P.R., Fritz, Deborah, and Maxwell, J, 1984, Glaucophane schists and ophiolites of the northern California

Coast Ranges: Isotopic ages and their tectonic implications: *Geological Society of America Bulletin*, v. 95, p. 1373-1382.

Raney, J.A., 1974, Geology of the Elk Creek-Stonyford area, northern Caalifornia; Ph.D. thesis, University of Texas at Austin.

Robertson, A.H.F., 1990, Sedimentology and tectonic implications of ophiolite-derived clastics overlying the Jurassic Coast Range ophiolite, northern California: *American Journal of Science,* v. 290, p. 109-163.

Sarna-Wojicicki, A.M., Meyer, C.E., Bowman, H.R., Hall, N.T., Russell, P., Woodward, M.J., and Slate, J.L., 1985, Correlation of the Rockland ash bed, a 400,000-year-old stratigraphic marker in northern California and western Nevada, and implications for middle Pleistocene paleogeography of central California: *Quaternary Research*, v. 23, p. 236-257.

Shervais, J.W., and Kimbrough, D.L., 1985, Geochemical evidence for the tectonic setting of the Coast Range ophiolite: A composite island arc-oceanic crust terrane in western California: *Geology*, v. 13, p. 35-38.

Suppe, John, 1973, Geology of the Leech Lake Mountain-Ball Mountain region, California; a cross section of the northeastern Franciscan belt and its tectonic implications: University of Calif., Berkeley, *Publications in Geological Sciences*, v. 107, 82 p.

Unruh, J.R., Ramirez, V.R., Phipps, S.P., and Moores, E.M., 1991, Tectonic wedging beneath fore-arc basins: ancient and modern examples from California and the Lesser Antilles: *GSA Today*, v. 1, no. 9, p. 185-190.

van der Berge, J.C., 1968, The paleo-geomorphological features of the Lovejoy Formation in the Sacramento Valley, California: Unpubl. M.S. thesis, Davis, California, University of California, 144 p.

Wentworth, C.M., Blake, M.C., Jr., Jones, D.L., Walter, A.W., and Zoback, M.D., 1984, Tectonic wedging associated with emplacement of the Franciscan assemblage, California Coast Ranges: *in* Blake, M, Jr., ed., Franciscan Geology of northern California: *Society of Economic Paleontologists and Mineralogists, Pacific Section*, v. 43, p. 163-173.

Wilson, T.A., 1961, The geology near Mineral, California: University of California, Berkeley, M.S. thesis, 94 p.

Worrall, D.M., 1981, Imbricate low-angle faulting in uppermost Franciscan rocks, south Yolla Bolly area, northern California: *Geological Society of America Bulletin*, v. 92, p. 703-729.

## DESCRIPTION OF MAP UNITS

### SACRAMENTO VALLEY-WESTERN FOOTHILLS PROVINCE

t **Dredge tailings (Holocene)**--Also includes other ground disturbed by man

Qsc **Stream channel deposits (Holocene)**--Gravel, sand, and silt deposited in open, active stream channels without permanent vegetation. These deposits are being transported under modern hydrologic conditions; consequently they are light tan and gray, unweathered, and usually in contact with modern surface waters. Thickness varies from 25 m on the Sacramento River to less than a few centimeters in bedrock canyons

Qa **Alluvium (Holocene)**--Gravel, sand, and silt derived from the Tehama and Tuscan Formations and rocks in the Coast Ranges and Klamath Mountains deposited by present-day stream and river systems. Differ entiated from older and younger units chiefly on geomorphic position in modern stream channels

Qo **Overbank deposits (Holocene)**--Sand, silt, and minor lenses of gravel deposited by floods and high-water stages on low terraces adjacent to present-day alluvial channels

Qao **Mixed alluvial and overbank deposits (Holocene)**--Gravel, sand, and silt deposited by normal and high-water flows in modern streams

Qb **Basin deposits (Holocene)**--Fine-grained silt and clay

Qls **Landslide deposits (Holocene)**--Slumped, chaotic mixtures of underlying bedrock units and colluvium

**Modesto Formation (Holocene and Pleistocene)**--Divided into:

Qmu **Upper member**--Gravel, sand, silt, and clay lithologically similar to the lower member but does not have pedogenic B-horizon. Both the upper and lower members probably were deposited by the same stream systems that flow today because they generally border existing channels and are less than 3 meters thick

Qml **Lower member**--Alluvium composed of gravel, sand, silt, and clay. Soils on the lower member contain a pedogenic B-horizon. Terraces display very fresh despositional morphology with little if any erosional features. Unit is less than 3 meters thick

**Riverbank Formation (Pleistocene)**--Divided into:

Qru **Upper member**--Gravel, sand, silt, and clay lithologically similar to the Modesto Formation but differentiated from it by geomorphic position above the Modesto terraces and greater degree of soil formation. Soils display medial development with strong textures, B-horizons, and local hardpans. The upper member of the Riverbank Formation occurs on geomorphically lower and generally smoother terrace surfaces than the lower member. It is lithologically very similar to, but more widespread than, the lower member of the Riverbank. The soil profile on the upper member is not as well developed as that on the lower member. Unit is less than 10 meters thick

Qrl

**Lower member**--Gravel, sand, silt, and clay derived from heterogeneous, metamorphic, sedimentary, and volcanic rocks; lithologically similar to the Red Bluff Formation, but slightly finer grained and contains less gravel. The lower member is more eroded than the upper member and it occurs on the higher of two terraces cut and filled into surface of the Red Bluff Formation

Qr

**Rockland ash bed (Pleistocene)**--Loosely aggregated, dacitic pumice lapilli ash (Wilson, 1961) that contains scattered, coarse, white pumice fragments. Occurs in northeast part of map area, east of Laniger Lakes, as scattered erosional remnants of a large non-welded ash-flow sheet that erupted northeast of the map area. Pumiceous fragments are composed primarily of silky white, wispy, vesicular glass that contain scattered crystals of glassy to white plagioclase and sanidine, green hornblende, hypersthene, and minor magnetite. Thickness about 4 m. Fission track age of 0.4 m.y. (Sarna-Wojicki and others, 1985)

Qrb **Red Bluff Formation (Pleistocene)**--Very coarse red (2.5-25YR) gravel with minor amounts of interstratified sand and silt. Red Bluff deposits located west of the Sacramento River in this map area were derived from the Coast Ranges. Volcanic-clast conglomerate in the northeast part of the map area was derived from the Tuscan Formation and lava flows and is correlated with the Red Bluff Formation to the west. Quaternary alluvial units were deposited in channels eroded into the Red Bluff Formation. The Red Bluff Formation is overlain by the Rockland Ash bed (0.4 m.y.) and it overlies the basalt of Deer Creek (1.08 m.y.; Harwood and others, 1981) 25 km southeast of the city of Red Bluff. Maximum thickness 5 m

Tte **Tehama Formation (Pliocene)**--Fluvial deposits of pale-green, gray, and tan sandstone, tuffaceous sandstone, and siltstone with lenses of crossbedded pebble and cobble conglomerate derived from rocks of the Coast Ranges, Klamath Mountains, and the Tuscan Formation. As mapped, includes the Nomlaki Tuff Member at or near its base. Interfingers with Tuscan Formation in the approximate vicinity of the Sacramento River. Maximum thickness is about 500 m near the city of Willows

Tten **Nomlaki Tuff Member**--White, light-gray, locally reddish-tan to pink dacitic pumice tuff and pumice lapilli tuff at or very near the base of the Tehama Formation. Pumice fragments, as much as 20 cm in diameter, are generally white in the lower part of the member and a mixture of white, light- and dark-gray in the upper part. Member is generally a massive, non-welded, nonlayered ash-flow tuff well exposed at Hayes Hollow, Stone Valley, Thomes Creek and at numerous localities to the north and east (Blake and others, 1984). Maximum thickness 25 m. The age of the Nomlaki is given by Evernden and others (1964) as 3.4 m.y.

Tl **Lovejoy Basalt (Miocene)**--Black, dense, hard, microcrystalline to extremely fine-grained, equigranular to sparsely porphyritic basalt. Where porphyritic, it contains scattered phenocrysts of plagioclase and lesser amounts of clinopyroxene in an hypocrystalline groundmass of felted plagioclase microlites, intergranular clinopyroxene, olivine and magnetite, and intersertal grayish-green to black, opaque basaltic glass. It is everywhere highly fractured with distinctive concoidal fracture surfaces. The Lovejoy Basalt caps the Orland Buttes on the west side of the valley and Table Mountain at Oroville on the east side of the valley. The Lovejoy is penetrated by numerous wells in the valley (van der Berge, 1968) where a narrow linear subsurface distribution pattern strongly suggests that the Lovejoy flowed in a channel or channels across the present site of the Sacramento Valley

The maximum thickness at Orland Buttes is about 20 m. Dalrymple (1964) estimated the age of the Lovejoy to be early Miocene (between 22.2 and 23.8 m.y.)

**Great Valley sequence (Late Cretaceous)**--Marine sedimentary rocks of the Great Valley sequence Cenomanian-Campanian?) Unconformably overlie basement rocks of the Sierra Nevada

Kms **Mudstone (Late Cretaceous)**--Dark-gray mudstone with minor thin interbeds of siltstone and fine-grained sandstone

Kss **Sandstone and conglomerate (Late Cretaceous)**

**Elder Creek terrane**--Divided into:

ecms **Mudstone (Late Cretaceous to Late Jurassic)**--Dark-gray mudstone, hackly fractured, with minor tan siltstone and sandstone. Limestone nodules, lenses, and thin beds locally abundant. Relatively nonresistent unit forms valleys parallel to strike ecss

**Sandstone and conglomerate (Late Cretaceous to Late**
conglomerate. Contains minor interbedded mudstone. Relatively resistant unit forms prominent topographic ridges parallel to strike

**Coast Range ophiolite (Middle and Late Jurassic)--**
Dismembered ophiolite consisting of:

ecbr

**Crowfoot Point ophiolitic breccia (Late Jurassic)--**
and blocks of ultramafic rocks, gabbro, diabase, basalt, plagiogranite, and scarce radiolarian chert

ecdg

intrusive diabase, gabbro, and plagiogranite plus scarce extrusive basalt

ecg

**Layered gabbro**--Alternating layers of light-colored clinopyroxene and plagioclase with serpentinized olivine and orthopyroxene in more mafic varieties. In stream exposures, layering can be seen to be discontinuous and "cross-bedding" is common. Includes minor intercalations of layered ultramafic rocks

ecw

**Layered ultramafic rocks**--Dark layers of clinopyroxene orthopyroxene, ore, and olivine, with wehrlite, clinopyroxenite, and dunite in decreasing order of abundance. Includes minor layered gabbro

ech

**Harzburgite**--Strongly foliated, dark green to black ultramafic rock made up of serpentinized olivine and enstatite plus minor clinopyroxene and accessory chromite. Includes minor intrusive diorite and quartz diorite (dio)

ecsp **Round Mountain serpentinite melange**--In this area contains blocks of basalt, radiolarian chert, diabase, and gabbro (all mapped as g) in a sheared matrix of serpentinized dunite and harzburgite. Locally contains small intrusive bodies of diorite and quartz diorite (not mapped separately) plus small (5-10 m) blocks of amphibolite and garnet amphibolite (x) and rare blueschist (♦)

**Smith River subterrane of Western Klamath terrane--**

srs **Metasedimentary rocks (Late Jurassic?)**--Dark slaty to phyllitic shale, metagraywacke, and minor stretched-pebble conglomerate. Unfossiliferous. Probably part of the Galice Formation of Oxfordian to Kimmeridgian age. Includes minor intercalations of metavolcanic rocks not mapped separately

## COAST RANGES PROVINCE

Qls **Landslide deposits (Holocene and Pleistocene)**

Qg **Glacial deposits (Pleistocene)** (see De Wit, 1990)

## Eastern Franciscan Belt

**Pickett Peak terrane**--Divided into:

ppsm mb — **South Fork Mountain Schist (Early Cretaceous metamorphic age)**--Intensely crumpled and quartz-veined mica schist. Includes fine-grained, laminated, greenish-bluish metabasalt(mb) plus local metachert (not mapped separately)

ppv mv — **Valentine Spring Formation (Early Cretaceous metamorphic age)**--Dominantly metagraywacke of textural zone 2B ($ppv_2$) and 3A ($ppv_3$) of Jayko and others (1986). Includes minor schistose metavolcanic rock(mv) and rare metachert (not mapped separately)

**Yolla Bolly terrane**--In this area, divided into:

ybt ch gs — **Taliaferro Metamorphic Complex (Early Cretaceous to Middle Jurassic?)**--Includes schistose jadeite-bearing metagraywacke, crumpled phyllite, glaucophane-bearing metagreenstone(gs) and metachert(ch). Metachert contains Late Jurassic radiolarians at one locality (unpublished data, D. L. Jones)

ybc ch gs — **Chicago Rock melange (Early Cretaceous to Middle**

**Jurassic)**--Mostly sheared argillite, graywacke, and conglomerate with abundant blocks of fine-grained greenstone(gs) and chert(ch). Includes scarce serpentinite, rare blueschist, and amphibolite knockers (unmapped). Radiolarians extracted from chert are Middle Jurassic to Early Cretaceous in age. Scarce *Buchias* are of Berriasian and Valanginian ages. Terrain commonly characterized by grass-covered hillsides

ybh ch **Metagraywacke of Hammerhorn Ridge (Early Cretaceous to Middle Jurassic)**--Dominantly graywacke with lesser amounts of argillite and conglomerate and abundant interbeds of chert(ch) which yield fossils of Early Cretaceous to Early Jurassic age. Includes scarce, intrusive diabase-gabbro (not mapped separately). Generally forms resistant ridges and is commonly timber covered

ybhm **Metagraywacke of Hull Mountain (Middle Cretaceous?)**Dominantly graywacke with lesser amounts of argillite and conglomerate. Minor interbeds of chert(ch) which yield fossils of Cretaceous age. Except for age, appears identical to Hammerhorn Ridge unit

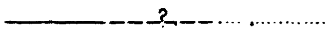
ybsm **Metagraywacke of Sanhedrin Mountain (Early**

**Cretaceous to Middle Jurassic)**--Dominantly graywacke with minor argillite and conglomerate, abundant, thick lenses of chert, and scarce intrusive greenstone although graywacke and argillite are the only rock types found in the Willows quadrangle

ybu **Undivided part (Lower Cretaceous and Upper Jurassic)**--Broken formation with metagraywacke and rare chert similar to that of other units of the Yolla Bolly terrane; may be equivalent to either/or unit ybh or unit ybc

**Central Franciscan Belt**

cem **Melange (Cretaceous to Upper Jurassic)**--Argillite-matrix melange locally containing blocks of greenstone(gs), radiolarian chert(ch), blueschist or eclogite(bs), amphibolite(amph), ultramafic rocks and serpentinite (sp)

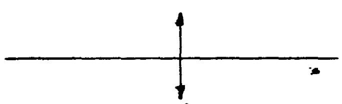



Contact - Dashed where approximately located; queried where uncertain; dotted where concealed

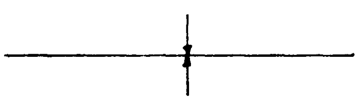

Steeply dipping fault - Dashed where approximately located; queried where uncertain; dotted where concealed.


Low-angle normal (detachment) fault


Thrust fault - Dashed where approximately located; queried where uncertain; dotted where concealed

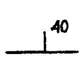


Anticline

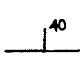


Syncline

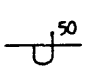
Strike and dip of beds




inclined




inclined, top known




overturned

Strike and dip of foliation


inclined

vertical

Strike and dip of bedding and foliation

inclined

Approximate location of stage boundaries

Textural zone boundaries

Approximate location of suspected fault separating sedimentary rocks of Elder Creek terrane and Great Valley sequence deposited on Sierran basement

Stage boundaries within the Great Valley sequence

base of Turonian

base of Cenomanian

base of Albian

top of *Buchia* beds

J/K boundary

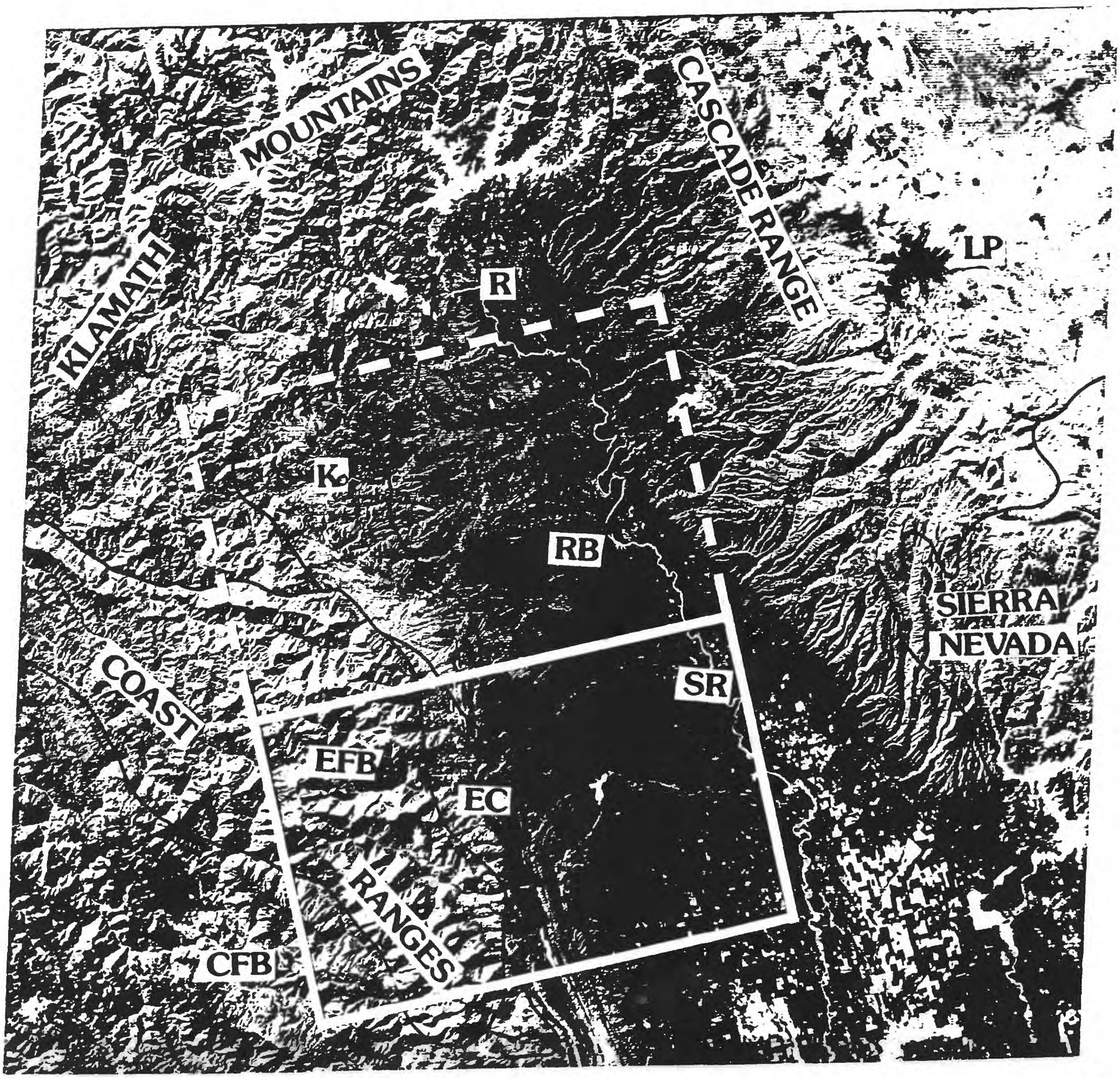



Fig. 1 LANDSAT image showing location of Willows (solid border) and Red Bluff (dashed border) 1:100,000 quadrangles and main tectonic and geopgraphic features. CFB=Central Franciscan belt, EFB=Eastern Franciscan belt, KM=Klamath Mountains, GV=Great Valley, K=Cretaceous overlap sequence, EC=Elder Creek terrane, SN=Sierra Nevada, CR=Cascade Range, C=Chico, R=Redding, RB=Red Bluff, SR=Sacramento River, LP=Lassen Peak.

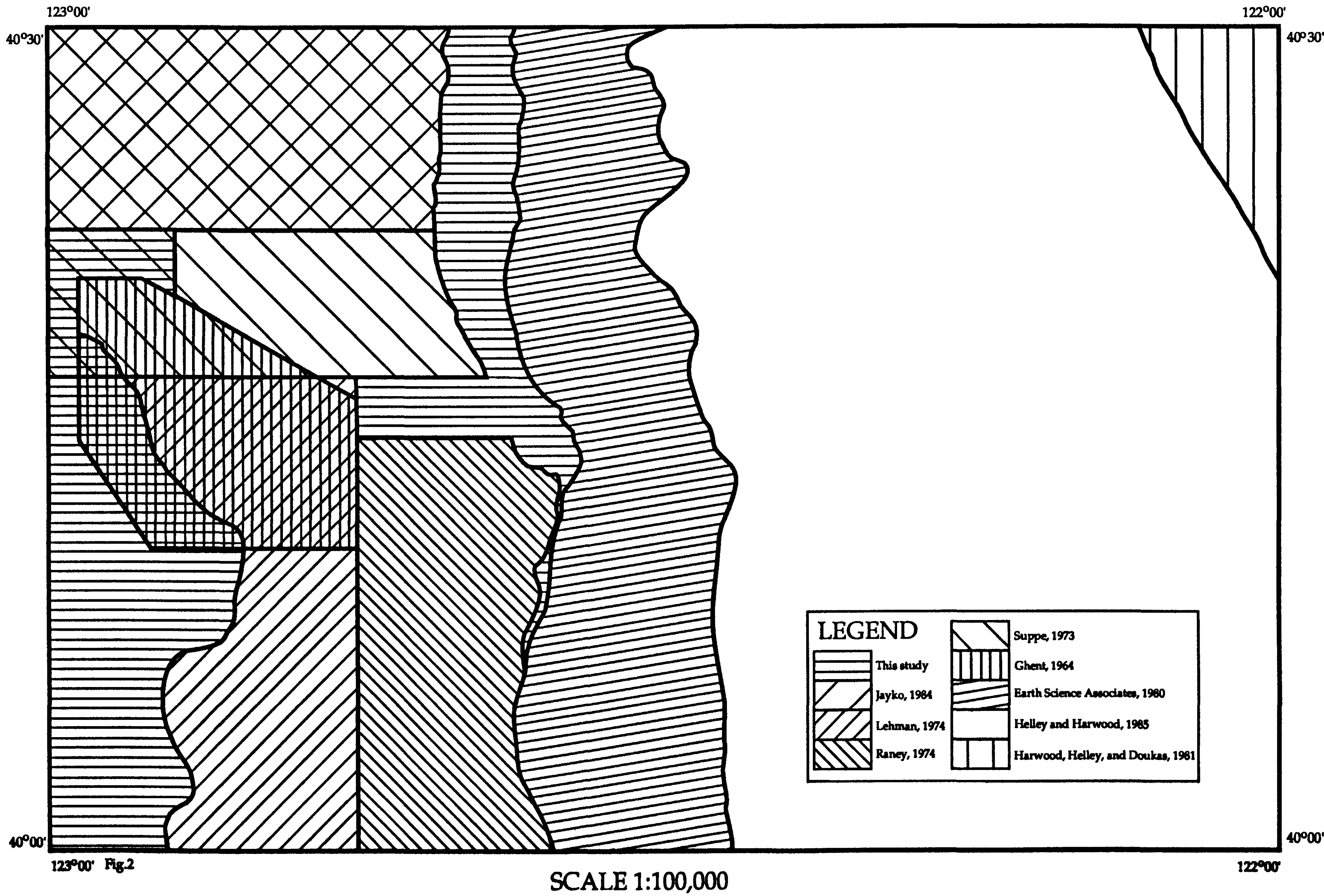



Fig. 2 Index to published mapping in the Willows 1:100,000 quadrangle

# CORRELATION OF MAP UNITS

(*SEE DESCRIPTION OF MAP UNITS FOR EXACT AGE ASSIGNMENTS)