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LASSEN VOLCANIC
NATIONAL PARK

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LASSEN VOLCANIC NATIONAL PARK
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et beds beneath an unconformity, and offset structures, we deduced that part of the basin has been transported about 65 km west-southwesterly to its present position by displacement on the complex system of lateral faults. Some faults, with good examples in the Frenchman Mountain and Muddy Mountain blocks, can be shown to change along strike from left-slip through normal to right-slip as their strike directions change through as much as 140°; these changes suggest an integrated movement pattern that is consistent with generally east-west to southwest extension and westerly to southwesterly tectonic transport.

Areas adjacent to the deformed basin on the south and extending southeast and east to the edge of the Colorado Plateau experienced extreme extension during the period of major lateral slip. We interpret the main normal and lateral faulting to be a surficial expression of large-scale southwest motion of mantle material along the Colorado Plateau boundary and extending into the Basin and Range province.

SMALL SCALE MOVEMENTS OF EARTH FISSURES IN SOUTH-CENTRAL ARIZONA

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Bimonthly horizontal strain measurements of fissures have been made at seven dial gauges near Signal Peak, Picacho Mountains, and in Avra Valley, Arizona. A Pyrex glass rod is fixed on one side of a fissure and pushes against a dial gauge fixed to the other side. Installations are in shallow covered trenches. Movements ranging from 5 µm to 25 mm are detected with a measurement error of less than 5 µm. Fissures have been observed to open and close repeatedly. With one exception, old and new cracks showed no pronounced difference in character. The maximum opening rate was 4.1 µm hr⁻¹ over a 17-day period, and the maximum closing rate was 5.0 µm hr⁻¹ over a 14-day period. Following a severe storm, one fissure abruptly opened 31 mm within a 14-hour period while one nearby parallel fissure opened 1.6 mm and another nearby parallel fissure closed 2.1 mm.

Transducer measurements of horizontal movements across fissures of up to 4 hours' duration were made with a resolution of 10 nm. Simultaneous measurements of horizontal linear strain in nearby unfissured soils provided controls. In Avra Valley the greatest rate of fissure closing was 8.7 µm hr⁻¹ across a span of 95 cm, while the control installation exhibited a compressive strain rate of 2.3×10^{-6} hr⁻¹.

Greatest rate of fissure opening was 3.8 µm hr⁻¹ over an 86 cm span; the control dilated 0.43×10^{-6} hr⁻¹. At a breached section of Chicken Dam, the greatest opening and closing rates were 6.0 µm hr⁻¹ and 10 µm hr⁻¹ over a 76 cm span. In most cases at both locations, the fissure movement and control strain were in the same sense and the movement was smooth.

MID-TERTIARY VOLCANIC GEOLOGY OF THE NORTH-CENTRAL PART OF THE HOGGOLLO-BATIL VOLCANIC FIELD, NEW MEXICO

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The area of this study (the Crosby Mountains and vicinity), is north of the San Augustin Plains, a major northeast trending graben. Over 30 volcanic and volcanoclastic units have been mapped and in general consist of: (1) a lower succession of interbedded andesitic mudflow breccia, volcanoclastic sediments, and andesite lava flows; (2) a middle succession, primarily of interbedded quartz latite to rhyolite ash-flow tuff and volcanoclastic sediments, with lesser amounts of intertonguing basaltic andesite and andesite lava flows, rhyolite lava flows and domes, rhyolitic tuff-breccia, and minor interbedded air-fall tuff and pumiceous ash-flow tuff; and (3) an upper succession of basaltic andesite to quartz latite lava flows and minor intrusions. The ash-flow tuffs of the middle succession are divisible into three groups of decreasing age: (A) K-feldspar-rich, moderately crystal-rich; (B) plagioclase-rich, systematically crystal-poor to crystal-rich; and (C) K-feldspar-rich, crystal-poor. Flow directions indicate that the ash-flow tuffs were erupted from a number of known and unknown sources. Most of the sources are outside this area except for a speculative volcano-tectonic depression consisting of a basin filled with volcanic and volcanoclastic rocks (the Crosby Mountains depression) and associated (7) tuff-breccia zone, rhyolite domes, and a central structural dome. A number of other volcanic sources have been identified, the most important of which is the Horse Mountain andesite to quartz latite composite volcano.

PLEISTOCENE VOLCANISM NEAR LASSEN PEAK, CALIFORNIA

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Geologic field mapping combined with radiometric dating and preliminary petrologic studies reveal the history of Pleistocene volcanism near Lassen Peak. Chemical analyses of 65 samples show SiO₂ ranging from 49 to 70 wt.%, K₂O 1.3 wt.% at 60% SiO₂, and FeO/MgO consistently 10:1. 2. Dacite, two-pyroxene andesite, and minor olivine andesite form a broad platform in the eastern part of the area and an eroded andesitic volcano (Mt. Tehama) in the west; dacite and rhyolite occur as flows and domes in the north. There have been at least 5 major episodes of volcanism in the area: (1) the oldest exposed flows (1,592.01 m.y.) are dacite which, together with 2-pyroxene andesite flows and pyroclastics, form the base of Mt. Tehama and of the platform; (2) the second episode produced dacite at 484.01 m.y. on the platform and 2-pyroxene

andesite now exposed in the eroded core of Mt. Tehama; (3) volcanic activity shifted to a new vent 2 km. west of the main Sulphur Works vent and produced olivine- and 2-pyroxene andesite as well as a greater proportion of pyroclastic material; (4) the last eruptions from the Sulphur Works vent were 2-pyroxene andesite flows and pyroclastic flows, and (5) a long pause in eruptive activity ended when a voluminous, gas-rich biotite-hornblende rhyolite flow issued from a new vent now occupied by Lassen Peak. During the last 250,000 years 3 dacite domes have been extruded in an east-west band from the northern margin of the platform to the north flanks of Mt. Tehama, and a high-Al basaltic shield volcano was emplaced on the southern part of the platform. Volcanic vents, thermal features, and the two major streams draining the southern part of Lassen Volcanic National Park follow northwest-southeast and north-south trends that intersect near the recently active volcanic centers of Lassen Peak and Chaos Crags.

STABLE ISOTOPE STUDIES OF CA-MG(Fe)-AL-SI SKARNS, ELKHORN, MONTANA

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Stable C-H-O isotope and petrologic studies have been conducted on the mineralogically zoned Ca-Mg(Fe)-Al-Si contact skarns at Elkhorn, Montana. Applications of P-T-X_e equilibria and oxygen isotope thermometry to skarn mineral assemblages fix main-stage skarn formation to $P = 1.0 \pm .3$ kbar, $T = 525 \pm 30^\circ\text{C}$, $X(\text{CO}_2) = .05$ to $.30$, $\log f(\text{O}_2) = -25$ to -20 , $\log a(\text{SiO}_2) = -.02$ to 0.0 . Calculated $\delta^{18}\text{O}$ and δD ranges for H₂O are: Intrusive (+6.9 to +8.2‰); Skarn (+9.0 to +12.5‰); Marble (+19.7 to +22.5‰). The data clearly indicate that the skarn fluids were dominantly magmatic in origin; significant influxes of meteoric H₂O are precluded for the main part of skarn formation. This contrasts with the relatively early influx, and later dominance by meteoric H₂O in the Osgood Mountains, Nevada, skarns (Taylor and O'Neil, 1977). Mass balance calculations, which indicate that observed $\delta^{18}\text{O}$ values in the skarns (-5.1 to -8.7‰) are too low to have been due to decarbonation of preexisting marble (-1.1 to -2.6‰), infer a magmatic source for skarn C. Fluctuations in $X(\text{CO}_2)$ from .05 to .20 are indicated by mineralogical variations and suggested by the positive correlation of skarn $\delta^{18}\text{O}$ with these petrologically defined changes in $X(\text{CO}_2)$. The variable O^{18} enrichment (.8 to 4.3‰) in skarn relative to magmatic fluids suggests that this $X(\text{CO}_2)$ variation is the result of progressive mixing of magmatic H₂O (+8‰) with CO_2 (+28‰) evolved in marble to skarn transformations. The resultant $X(\text{CO}_2) = .25$ required by the oxygen isotope data for such mixing is compatible with experimental T-X(CO₂) stability fields for the observed assemblages. Stable isotope data from Elkhorn appear to reflect changes in T-X_e conditions within the skarns and therefore offer one means of investigating skarn-forming processes.

UNUSUAL PELECYPODS FROM THE PERMIAN OF ARIZONA AND NEW MEXICO

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Permian carbonates of Arizona and New Mexico contain an unspectacular record of marine invertebrates, including numerous pelecypod genera common to shelf deposits of similar age in many parts of the world. In contrast to these cosmopolitan, generalized forms, two unusual bivalves exhibit unique specializations and limited geographic distribution.

Scaphellina concinna, common locally in the Gamma Member of the Kaibab Limestone of central Arizona, is a robust, highly specialized deep burrower with prominent pallial sinus and posterior gape. It is the only representative of its family, and is known only in Arizona and Wyoming (Park City Fm.).

Pseudomonotis (Trenaticoncha) likharevi is a very large bivalve amazingly similar to modern oysters in general form. It possessed a byssal opening throughout life, but this changed during growth from a pectinoid notch to a peculiarly isolated Anomia-like circular aperture. Unlike true oysters, the shells were uncemented and rested with the flattened right valve lowermost. The species is common to scattered localities in the San Andres Formation of New Mexico, the Kaibab Limestone of Arizona, and the Park City Formation of Wyoming. Related species in the West Texas reefs were more oyster-like in their cemented mode of life and complete loss of the byssus.

STRUCTURAL EVOLUTION OF THE SOUTHEAST CANADIAN CORDILLERA

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The Shuswap metamorphic core complex of the Southeast Canadian Cordillera, which is allochthonous with respect to a fixed reference frame beneath the Plains of the North American craton, evolved and became consolidated prior to major development of thrust faulting in the Rocky Mountains.

Polyphase deformation of the infrastructure of the complex beneath a weakly compressed suprastructure is probably due to shear strains generated by underthrusting of marginal lithosphere rather than to gravitational upwelling and lateral spreading.

Pre-metamorphic to early metamorphic strain of the complex may be related to eastward underthrusting from the west. Late metamorphic strain may be related to westward underthrusting of the North American craton to the east. Continued under-

PLEISTOCENE VOLCANISM NEAR LASSEN PEAK, CALIFORNIA

① (*) Lassen Peak, a large dacite dome in northern California, is now the most prominent volcano at the southern tip of the Cascade Range, but it actually represents the latest stages of volcanic activity in an area dominated by stratovolcanoes for the last

② (*) 2 m.y. Most of the composite cones in this end of the Cascades, 25 km NW of plutonic and metamorphic rocks of the northern Sierra Nevada, have been eroded down to unrecognizable remnants and are represented by thick andesitic lahar deposits such as the Tuscan Formation exposed west of Lassen Peak. Tuscan rocks probably form the base on which the younger volcanics I have studied accumulated.

③ (*) Enough of a stratocone remains south of Lassen Peak, however, to enable us to imagine Mt. Tehama towering over the dacite domes which now dominate the landscape. Howel Williams called the old mountain Brokeoff Volcano in his excellent study of the geology of Lassen Volcanic National Park in 1932, and John Fountain called it Tehama in his 1976 investigation of the chemistry of the lavas in the southwest portion of the Park. This slide shows the U-shaped valley of Mill Creek, cut into rocks of the 3rd eruptive episode, and late stage flows in the distance.

④ (*) Mt. Tehama is located 200 km east of Cape Mendocino, which marks the location of a triple junction involving 2 transform faults and a shallow subduction zone where the Juan de Fuca plate is slowly moving under the N. American plate. (*) The volcanic activity of Mt. Tehama is presently confined to fumaroles and solfatarae within 2 belts, each about 1.5 km. wide and 13 km. long, trending NW-SE and NS. These belts coincide with the major drainage patterns from the central eroded part of Mt. Tehama.

My field work was supported by the Geothermal Program of the U. S. Geological Survey. The mapping has enabled me to recognize 7 episodes of volcanism, which I will now describe according to rock type, whole rock chemistry, and petrography. Radiometric ages on several units happily fit into the scheme of things. I classified the rock types on the basis of whole rock silica content, so that andesites contain 54-64% silica and dacites have up to 69%

silica.

This is a simplified geologic map of about 180 square kilometers just south of Lassen Peak. Here is the road through LVNP, for reference. The major areas of thermal activity are here (Sulphur Works, Bumpass, Little Hot Springs Valley, Morgan, Devil's Kitchen). The northern part of the area is dominated by dacite domes, including Lassen Peak off the map. Deep U-shaped valleys and glacial terrain extend to the west, south, and east. A ridge here, from Brokeoff Mt. toward Lassen Peak, is a ^(*)semicircular feature with a steep face which has been interpreted as a remnant of a caldera wall. My field work has not revealed any evidence in support of this idea, and in fact, from the air the ridge looks more like an arrête, a glacial feature, although the effect is somewhat blurred by intense alteration in the central area.

^(*) Altered areas are shown in an ivory color; alluvium and landslides are in yellow, and glacial deposits are grey. The succession of volcanic episodes as represented on this map is keyed to the following diagrams by the colors: purple shows the oldest rocks I found in the area, dated by the K-Ar technique at 590,000 years on a dacite here. This dacite and a thin olivine andesite flow above it were engulfed by late stage eruptions, shown in brown. Similar dacites and an olivine andesite flow are exposed deep in this valley in the central area, and other dacites and olivine andesite form a ridge and the base of the eastern platform area. The blue color shows the platform flows, K-Ar dated at their exposed base at 480,000 years on a dacite here and some andesites exposed in Mill Creek canyon here, K-Ar dated at 470,000 years. The youngest flows of this episode in the eastern platform contain olivine, while those exposed in the central area, close to the main vent do not. The third episode of volcanism, shown in green, includes more olivine-bearing andesite flows in its early stages; and is exposed in steep ^(*)cliffs in the central part of the eroded cone and as remnants of valley-filling flows to the south. None of these rocks were fresh enough to date by K-Ar methods nor silicic enough to attempt zircon separation for fission-track dating. This episode includes thick flow breccias and pyroclastic deposits, and there are numerous small dikes in the area close to the presumed vent. ^(*) The last stages

of the construction of Mt. Tehama are represented by this brown color, and again there is no radiometric control. Enough time had passed, however, for valleys to be well established and these were filled by hot mudflows in the last stages of eruption. This area (BFQ and west) is the only coherent part of the volcano's slopes which remains today; it consists of a succession of olivine andesite and pyroxene andesite flows topped by dacites and increasing pyroclastic deposits.

The orange color is a rhyodacite flow which is also exposed over 15.5 sq. Km. north of the map area and apparently was erupted from a vent now occupied by Lassen Peak. It is a very distinctive unit, glassy and containing biotite, hornblende, and enough zircon to attempt a fission track date. My first try has yielded an age of $300,000 \pm 100,000$ years. This is based on 9 tracks in 8 zircon crystals out of 180 total, so I have much more work to do before I can report a more precise age. Dacite domes, shown in pink, were extruded along the northern edge of the stratocone and the platform; one dome, the green here, produced a stubby pyroxene dacite flow which has been dated by K-Ar methods at 230,000 years. Another dome contains numerous andesitic inclusions which apparently affected the composition of the duplicates enough to yield disparate K-Ar ages of 250,000 and 700,000 years. (*) The pale brown area in the SE is a high-aluminum basaltic shield volcano which is one of several in the eastern part of LVNP. A maximum K-Ar age of 230,000 years was obtained on this basalt but the geomorphology of the mountain shows it to be much younger.

(12) The next 3 slides present major and trace element composition of whole rock samples, analyzed by XRF at UC Santa Cruz. They are color-coded to correspond with the map pattern, and eruptive sequence to remember is purple, blue, green, brown, orange, red. (*) Major element silica variation diagrams seem to show that the episodes within the eruptive sequence are related by some sort of differentiation scheme. The general pattern is one of smooth variation of major elements with increasing silica, except for the earliest episode, which is more silicic than the 2nd episode (in blue). But for each element you can see the progression through time, with the rocks becoming slightly more silicic with each episode, through the late stages of Tehama

to the dacite flows and domes. The rhyodacite flow begins at a position of high silica, and then the gap between andesites and dacites is filled in by the data on the dacite domes. The young basalts plot on the trend as well, but only 4 analyses are represented by these curves. Notice that for phosphorus, potassium, and Ti, the third episode, shown in green is slightly off the main trend.

13) * The lower half of an AFM diagram shows the smooth compositional trend of the Mt. Tehama rocks corresponding closely to the average Cascades compositional trend. The lack of iron enrichment in the rocks of Mt. Tehama is evident when you compare the colored fields to the Thingmuli trend. Both lines are from Carmichael, 1964. The rocks in the Lassen area, then, are a typical calc-alkaline suite.

14) * The TE analyses are shown as colored fields with individual data points marked as well, to give you an idea of how many analyses are represented here. There are fewer for the trace elements than for majors. The relative standard deviation of these values is 2-3% for all but Thorium, which is 9-14%. For the other TE, then, the relative positions of the colored fields are real. Again, the sequence begins with a small reversal in the earliest episodes, followed by increasing values to the final dacite eruptions. The third episode, shown in green, appears anomalous with respect to Rb and Y. The first order picture for whole rock chemistry, though, is one of smooth trends suggesting a common source magma, and a progression of eruptive episodes related by differentiation.

15) * This chart shows the phenocrysts present in the different volcanic episodes, with the oldest at the top. X means the mineral is always present as a phenocryst, (X) means usually present, - means present in a few samples, and 0 means always absent. The earliest flows differ from E to W in the relative amounts of orthopyroxene, magnetite, hornblende and quartz present. This difference is reflected by the silica contents as well, with the western rocks containing 63-69% SiO₂. The second episode, colored blue, also differs in phenocryst mineralogy from east to west, with the eastern platform andesites occasionally containing hbl and qz, while the western flows which are closer to the vent do not. Plagioclases are reversely zoned. The 3rd episode has about the same silica

range as the second but it contains more olivine, more mt and a trace of biotite in the latest flows. Its plag phenocrysts are also reversely zoned. It is possible that this episode, which also is subtly different from the others chemically, may have emptied a distinct magma chamber whose vent was located 2 km east of the main vent.

④ The final stages of Mt. Tehama became more silicic, progressing from olivine andesite to pyroxene andesite flows in the first stages and culminating in qz and hbl-bearing dacites mixed with many pyroclastic flows. The plag phenos show normal zoning. * The rhyodacite flows always contain normally zoned plag, mt and hbl, usually opx, bio and qz, and sometimes cpx. They are 75% glass shot with mt dust and rare sanidine microlites. * The pyroxene dacite dome and flow contain cpx and opx, burned hbl and bio, plus quartz, but no mt as phenocrysts. Other dacite domes, shown in pink, variably contain, in decreasing amounts, phenocrysts of opx, cpx, mt, hbl, bio and qz. The basaltic shield volcano has olivine, clinopyroxene and mt phenocrysts, with orthopyroxene appearing in later flows.

* Mineralogical studies are too preliminary to test differentiation schemes, but they do suggest some second order variation in processes involving the 3rd eruptive episode.

In conclusion, then, a generalized stratigraphic succession has been worked out for Mt. Tehama, based on field mapping and strengthened by radiometric dating of some fresh flows present in this heavily dissected volcano. Within this framework, plots of whole rock chemistry suggest subtle differences in at least one volcanic episode, but the general picture appears to be one of a common source and closed-system differentiation.

Earth Sciences Board, U.C.S.C.
Santa Cruz, California 95064
April 10, 1978

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APR 13 1978
LASSEN VOLCANIC
NATIONAL PARK

Dear Dick:

Last week I gave a talk at the Cordilleran Section meeting of the Geological Society of America, entitled: "Pleistocene Volcanism near Lassen Peak, California." I enclose the published abstract and a copy of the text of my talk. I will send you copies of the figures if I make any.

I have mineralogical studies to complete before I begin writing my dissertation, and I expect to finish up next fall. I will send you a copy of the thesis when it is completed.

I will probably come up to Mineral briefly this spring and summer and I will try to see you then. Has anything more been happening at Sulphur Works? I would appreciate hearing about new developments.

Sincerely,

Penney

Penelope A. Bowen