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RUBIDIUM-STRONTIUM GEOCHRONOLOGY OF PROTEROZOIC ROCKS FROM THE PECOS AND TRUCHAS METAMORPHIC TERRANES, NORTH-CENTRAL NEW MEXICO

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Abstract—Rubidium-Sr isochrons obtained from seven suites of supracrustal rocks (volcanic and sedimentary rocks now metamorphosed to amphibolite facies), four from the Pecos terrane and three from the Truchas terrane, yield a bimodal distribution of ages ranging from 1232 to 1730 Ma. The older ages, averaging near 1650 ma, are consistent with U-Pb ages from metarhyolites and pre-kinematic plutons and may represent formational ages. The younger ages range from 1384 Ma downward and are the product of one or more late thermal events superimposed on thorough resetting of Rb-Sr systematics by regional metamorphism. A mineral-separate age (1285.6 ± 8.7 Ma) from feldspar-muscovite schist may precisely date one late event. In micaceous schistose rocks, Rb-Sr systematics are dominated by the Rb-rich micas, producing whole-rock isochrons that are essentially identical to mineral isochrons. In micas, the blocking temperature for resetting Rb-Sr systematics appears to be similar to that for K-Ar. Rocks exhibiting reset Rb-Sr systematics are distinguished by the presence of a differentiated cleavage defined by abundant mica.

INTRODUCTION

All but the most recent geochronologic work on Proterozoic rocks of northern New Mexico has concentrated on plutonic rocks (U-Pb, Rb-Sr) or micas from pegmatites and granites (K-Ar) because of the conceptual, if not actual, simplicity of these systems. These rock types have yielded a variety of ages that are difficult to interpret. An alternate approach, taken in this Rb-Sr study and the $^{40}Ar/^{39}Ar$ study of Grambling and Dallmeyer (1990), is to examine directly the geochronologic information contained in metamorphic rocks and minerals. This study examines the detailed Rb-Sr systematics of seven such suites of metamorphic rocks, four from the Pecos terrane and three from the Truchas terrane. Whole-rock and mineral-separate isochrons from amphibolites and mica-schists provide constraints on the mobility of Sr and the temporal significance of Rb-Sr ages from amphibolite-facies regional-metamorphic terranes.

Geologic setting

The Pecos and Truchas terranes (Fig. 1) are part of a collage of at least six tectonostratigraphic terranes that comprise the Proterozoic metamorphic belt of northern New Mexico (Grambling et al., 1988; Grambling et al., 1989), a belt that crops out in uplifts scattered across an area of more than 75,000 km^2. Four of these terranes, including both examined in this study, experienced amphibolite-facies peak *P-T* conditions near the Al_2SiO_5 triple point (3.76 kbar, 500°C after Holdaway, 1971), whereas the remaining two experienced granulite-facies peak *P-T* conditions in excess of 6 kbar and 650°C.

Rocks exposed in the Pecos terrance, also called the Pecos greenstone belt (Robertson and Moench, 1979) or the Pecos Complex (Bauer and Williams, 1989), fall into one of three general classifications (Robertson and Moench, 1979; Moench and Robertson, 1980): metavolcanic, metasedimentary and metaintrusive. Metavolcanic rocks are dominantly mafic, although felsic rocks are present locally. Metasediments tend to be mafic, suggesting local derivation from the metavolcanics. Both metasedimentary and metavolcanic rocks are examined in this study. The internal structure of the Pecos Complex is complicated (Klich, 1983); there are few top-facing indicators, and even these may have been rendered useless by transposition (Grambling and Codding, 1982). The transition from the Pecos terrane to the Truchas terrane to the north is characterized by a major ductile shear zone with displacement exceeding 10 km; the Pecos terrane was thrust northward over the Truchas terrane along this shear zone (Grambling et al., 1988). In this study, only the northernmost edge of the Pecos terrane, in the vicinity of the shear zone, was sampled (Fig. 2). Here, supracrustal metamorphic rocks

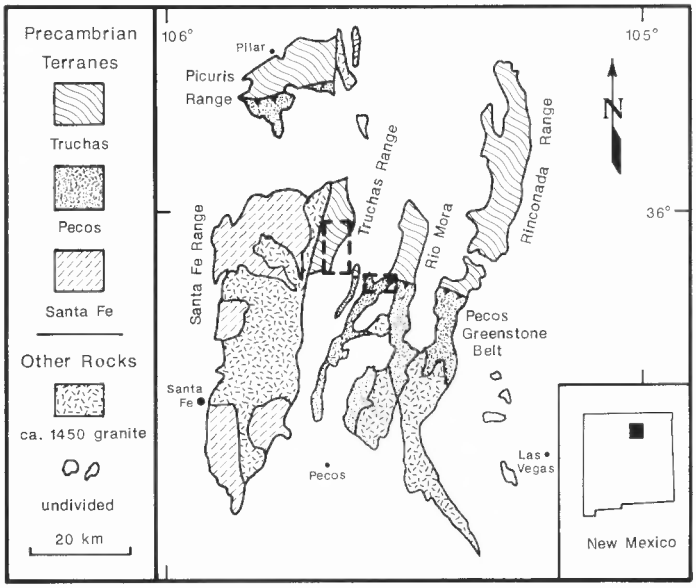


FIGURE 1. Three of the Proterozoic tectonic terranes of northern New Mexico (after Grambling, 1988; Bauer and Williams, 1989). Dashed boxes in the Truchas terrane and Pecos greenstone belt (Pecos terrane) denote the two areas sampled in this study.

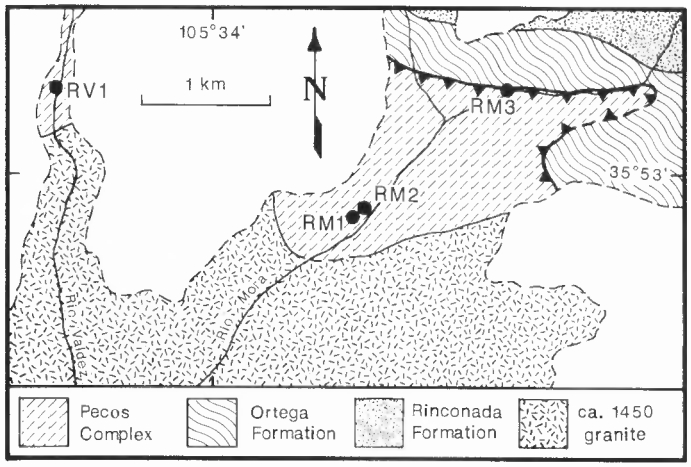


FIGURE 2. Geologic sketch map of the Rio Mora area of the Pecos terrane showing sampling locations for suites RV1, RM1, RM2 and RM3. Lack of shading denotes Paleozoic cover.

closely resemble rocks of the Vadito Group (Grambling et al., 1988; Bauer and Williams, 1989) and may be transitional to them.

The Truchas terrane in the study area (Fig. 3) is composed of the Hondo Group (Bauer and Williams, 1989) and the underlying Vadito Group. The Hondo Group consists of a sequence of quartzites and pelitic schists that exhibit a coherent internal stratigraphy (Grambling, 1979a; Grambling and Codding, 1982). The basal part of the Hondo Group is the Ortega Formation (Bauer and Williams, 1989), dominated by a 1000-m-thick massive, prominently crossbedded quartzite. The Ortega Formation also contains minor interbedded aluminous schist. It is overlain by the Rinconada Formation, composed of alternating layers of pelitic schist and quartzite, the highly graphitic Pilar Formation, and the Piedre Lumbre Formation, which contains interbedded pelitic and calcareous rocks. The units overlying the Ortega Formation have an aggregate outcrop thickness of ~500 m. One or more thrust slices, composed of felsic and mafic metavolcanic rocks of the Vadito Group, occur within the lower Ortega Formation (Grambling et al., 1988; Grambling, unpubl. mapping). At Truchas Peak, these thrust slices contain two distinct lithologies: a thick (up to 100 m) layer of snow-white quartz-muscovite-feldspar schist with minor but fairly continuous amphibolite layers, and a thinner member containing intercalated amphibolite and quartzite layers. Amphibolite layers are discontinuous on a regional scale. Both the schist and the amphibolites have been sampled for this study.

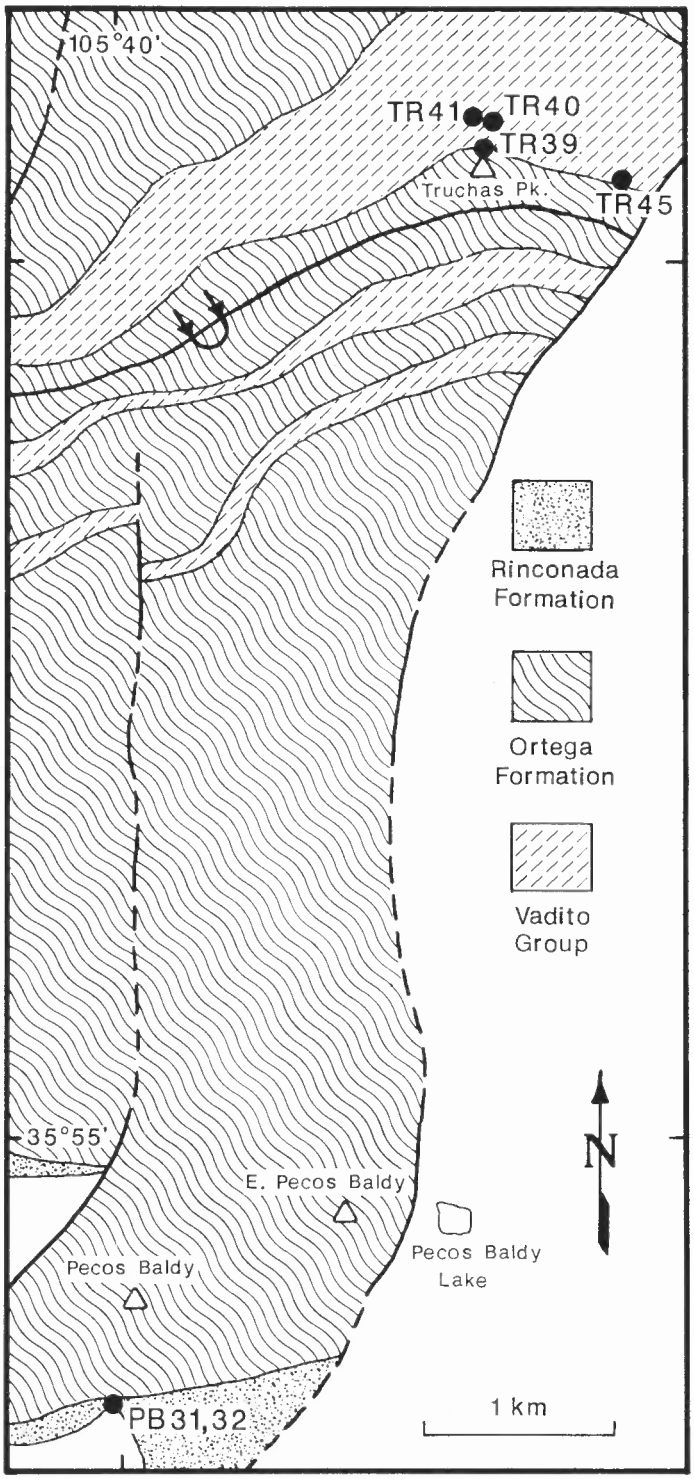


FIGURE 3. Geologic sketch map of the Truchas Peaks–Pecos Baldy area of the Truchas terrane showing sampling locations for suites TR39, TR40, TR41, TR45 and PB31, 32. Lack of shading denotes Paleozoic cover.

Microstructure and rock fabrics

Evidence of intense deformation can be found throughout both study areas (Grambling, 1979a, b, 1981; Grambling and Codding, 1982; Codding, 1983; Grambling et al., 1988; Robertson et al., in press). A foliation which lies parallel to bedding has been re-folded, producing tight to isoclinal map-scale folds that are associated with a steeply south-dipping axial-planar foliation. The axial-planar foliation, usually the most prominent one in outcrops, exhibits a characteristic differentiated cleavage composed of mm-scale layers of mica alternating with layers rich in quartz and feldspar. Grambling et al. (1988) and Robertson et al. (in press) have argued that these textural features developed in a single complex deformational event.

Other geochronologic work

Uranium-Pb dates on zircons from igneous rocks delineate the ages of primary igneous activity in the Proterozoic terranes of northern New Mexico. Supracrustal rocks, principally metarhyolites, yield U-Pb zircon ages between 1765 Ma and 1650 Ma (Stacey et al., 1976; Robertson and Moench, 1979; Bowring and Condie, 1982; Bowring et al., 1984; Reed, 1984). Later "anorogenic" granites give U-Pb and Rb-Sr ages near 1450 Ma (cf. Steiger and Wasserburg, 1966, 1969; Tilton and Grunenfelder, 1968; Long, 1974; Register and Brookins, 1979), and one or more late-stage thermal events are reflected in Rb-Ar ages from micas ranging from 1400 Ma to 1255 Ma (cf. Brookins, 1974; Brookins and Shafiqullah, 1975; Gresens, 1975; Brookins et al., 1977; Brookins and Laughlin, 1983). Recent $^{40}Ar/^{39}Ar$ plateau and isotope-correlation ages (Grambling and Dallmeyer, 1990; Thompson et al., in prep.) from metamorphic hornblendes fall in the range 1400–1440 Ma and for muscovite 1295–1400 Ma, ages interpreted to reflect the timing of peak metamorphism and a series of later lower-grade thermal events, respectively. Ages extant in the pre-1986 literature and relevant to the Proterozoic of northern New Mexico are compiled in Ward (1986).

METHODS

Sampling principles

Most samples in this study exceeded the rule-of-thumb whole-rock criterion by at least a factor of two (e.g., the minimum dimension of the sample was 20 times larger than the maximum dimension of the largest included crystal). Sampling of metavolcanic rocks was based on the premise that a given unit had uniform $^{87}Sr/^{86}Sr$ at the time of eruption and that the Rb/Sr ratio varied significantly throughout the unit. Suites of six to eight whole-rock specimens were collected from each outcrop, sampling areal extents ranging from a 3 m square to a 40 m traverse. Individual metavolcanic specimens were usually 8–10 cm across and were chosen so as to avoid veins and other visible signs of alteration wherever possible. Rocks presumed to be metasedimentary in origin were sampled differently, as there was no a priori reason to assume uniform initial $^{87}Sr/^{86}Sr$ throughout a given unit. A single 2 to 4 kg sample was collected, and small pieces of slightly varying mineralogy (still meeting whole-rock criteria) were cut from it.

Analytical procedures and data reduction

A detailed description of preparation methods is given in Ward (1986). Briefly, each field specimen was trimmed to remove weathered surfaces, cleaned ultrasonically to remove cutting debris, and then crushed to –100 mesh (whole rocks) or –60 mesh (mineral separates). Mineral separates were prepared using a combination of mechanical, magnetic and density separations, and were subsequently crushed to –100 mesh. Purity of each fraction was estimated visually after staining the feldspars. The sample powders were spiked with ^{87}Rb- and ^{84}Sr-enriched tracers, hydrothermally decomposed using reagent-grade HF and ultra-pure $HClO_4$, dried and redissolved in ultra-pure HCl, filtered through Whatman No. 5 filter paper to remove any insolubles, and Rb^+ and Sr^{2+} separated from other cations by ion-exchange chromatography using Dowex AG50W-X8 resin and 2.25 N HCl eluant. Rubidium and Sr concentrations and $^{87}Sr/^{86}Sr$ ratios were determined by isotope-dilution thermal-ionization mass spectrometry at the UNM Geochronology laboratory using standard techniques (Webster, 1960; Long, 1966; Van Schmus, 1966).

Replicate analyses of Eimer and Amend $SrCO_3$ gave $^{87}Sr/^{86}Sr = 0.70812 \pm 11$ (1σ) during the period that analyses were performed for all suites other than PB31 and PB32; for these two suites $^{87}Sr/^{86}Sr$ averaged 0.708020 ± 15 (1σ). Total analytical blanks were: Rb—5 ± 2 ng, Sr—25 ± 6 ng @ $^{87}Sr/^{86}Sr = 0.712 \pm 1$ (all precisions are $\pm 1\sigma$). The filter paper was the source of ~75% of the blank Rb and Sr.

External precision for measurements on unknowns was originally determined on replicate analyses of a wide variety of samples, but because of problems related to sample inhomogeneity and variable blank effects, these results gave a gross overestimate of analytical scatter. An alternate approach was adopted wherein external precisions were adjusted downward until several of the best isochrons of this study gave York model 1 *rMSWD* (root mean square of the weighted deviates) values sufficiently close to unity that probability of such deviations arising merely by chance exceeded 0.01. These calibration isochrons gave: RM3 (n = 7)—*rMSWD* = 0.58, *significance* = 0.01; RM2D wr-Ms-3Bt (n = 5)—*rMSWD* = 0.79, *significance* = 0.69; Truchas amphibolites (n = 9)—*rMSWD* = 1.09, *significance* = 0.94. With 15 degrees of freedom (n–2 for each isochron) the 1σ external precisions used in the following calculations were assumed to be: $^{87}Rb/^{86}Sr$—±0.50%, $^{87}Sr/^{86}Sr$—±0.025%. The $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ values used to calculate isochrons have been corrected for blank Rb and Sr, and their precisions reflect both uncertainties in blank values and the analyses themselves. Non-zero values of *r* (the error correlation coefficient) arise as a consequence of blank-subtraction, but are negligibly small.

Isochrons were regressed using the algorithm of York (1969) with weights inversely proportional to σ^2 errors in $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$. To perform these calculations, a program (Isochron v. 4.0) was written for MS-DOS computers using Borland's Turbo-C compiler and libraries (program available on request). Two regression models are used (after Ludwig, 1990): model 1, based on analytical errors only; and model 3, in which the scatter in $^{87}Sr/^{86}Sr$ is adjusted so that *rMSWD* = 1. The model 1 treatment is appropriate for isochrons in the strict sense (Brooks et al., 1972), whereas model 3 accommodates excessive scatter in the data (that which is not attributable to the analytical process) by assuming $^{87}Sr/^{86}Sr$ was not uniform at the time of closure of a suite of samples. Both models report scatter in age and initial ratio at the 95% confidence level; model 1 uses a small-sample t-multiplier based on the degrees of freedom of the determination of analytical precision (Brooks et al., 1972), whereas model 3 uses t for n–2 degrees of freedom (n = number of points in the regression) because the uncertainty for each point is determined from the data themselves rather than externally. In instances that *rMSWD* > 1, model 1 uses it as an additional multiplier of the 95% confidence interval, effectively decreasing analytical precision to the extent required to explain the observed scatter about the regression line. Model 1 also calculates *significance*, i.e., the probability that the data do indeed fit the regression line within the limits specified by analytical precision. If *rMSWD* >> 1, *significance* ≈ 0, and analytical precision drastically underestimates the scatter inherent in the data set; model 3 is a better choice for such data sets. In this study, model 1 is used only for isochrons with *significance* > 5% or *rMSWD* < 1; otherwise model 3 is used.

In model 3, geologic scatter, which is reported at the 1σ level, is added equally (not proportionally) to each point in the data set; this has a side-effect of increasing the relative weights of those points with high $^{87}Sr/^{86}Sr$. Geologic scatter can arise through several mechanisms other than variable initial $^{87}Sr/^{86}Sr$—open-system behavior and incomplete resetting during metamorphism are two possibilities. Consequently, model 3 ages should be viewed with some skepticism and corroborating evidence should be sought.

Isochron plots show 1σ error ellipses when these are significantly larger than the plotting symbols and also the 1σ error hyperbola of the regression line when it differs enough to be visible. All required constants for data reduction and isochron calculations were obtained from Weast (1974), Steiger and Jäger (1977) and Faure (1986).

Statistical significance of differences among pairs of values was calculated using one-tailed t-tests to assess the validity of the null hypothesis: "Both values come from populations with identical means." The mean (μ) is chosen so that the significance of each value is identical with respect to its estimated uncertainty and associated degrees of freedom. The probability that the null hypothesis is true is thus the product of the probabilities of both values that they each belong to populations with mean μ.

K-Ar ages

K-Ar analyses were obtained commercially on –60 mesh mica fractions. Ages were calculated using the constants of Steiger and Jäger (1977). Detailed analytical data are available in Ward (1986).

SAMPLE DESCRIPTIONS

Seven suites of samples, four from the Pecos terrane and three from the Truchas, were collected for Rb-Sr analysis. These areas have been mapped at a scale of 1:12,000 by Codding (1983) and Grambling (1979b, and in prep.), respectively. Precise coordinates and brief descriptions of the sampling sites are given in Table 1, and geologic sketch maps of the sampling areas have been presented in Figures 2 and 3. For succinctness, mineral names are abbreviated as follows: apatite—Ap, biotite—Bt, chlorite—Chl, epidote—Ep, feldspar—Fsp, garnet—Gt, hornblende—Hb, muscovite—Ms, plagioclase—Pl, potash feldspar—Kfs, quartz—Q and staurolite—Stl.

Pecos terrane

Suite RM1, collected at the base of the northwest wall of the canyon of the Rio Mora ~1 km below the confluence of the Rio Mora with the creek draining Bordo del Medio, consists of four samples of a medium-grained dark-gray amphibolite collected from a single outcrop approximately 3 m by 3 m. These rocks are composed of coarse Hb crystals with interstitial Q, Pl and minor Bt. Thin (<3 mm) discontinuous Q + Pl layers define an early foliation and in some places trace out fold noses, suggestive of transposition. Hornblende needles are weakly aligned, imparting a faint lineation. Alteration ranges from

TABLE 1. Latitudes and longitudes of sampling locations.

Suite	N Latitude	W Longitude	Site Description
RM1	35° 52'49.2"	105° 33'19.5"	Base of NW wall of Rio Mora valley @ 9,600' elev., 200 m NE of Bordo del Medio pack trail.
RM2	35° 52'51.7"	105° 33'16.4"	Approx. 75 m NE of RM1 outcrop.
RM3	35° 53'15.9"	105° 32'38.4"	Base of NW wall of Rio Mora valley, 0.6 km upstream from confluence with drainage from Bordo del Medio.
RV1	35° 53'16.5"	105° 34'41.7"	Trailside outcrop @ 9,750' elev. on W bank of Rio Valdez.
TR39	35° 57'49.2"	105° 38'36.4"	Approx. 150 m NNE of Truchas Peak @ 12,760' elev.
TR40	35° 57'52.3"	105° 38'37.9"	On N ridge of Truchas Peak @ 12,850' elev.
TR41	35° 57'53.6"	105° 38'40.1"	Approx. 75 m N of TR40.
TR45	35° 57'42.4"	105° 37'56.9"	N slope of E arête of Truchas Peak @ 11,860' elev.
PB31,32	35° 54'08.6"	105° 40'00.0"	Top of cliff overlooking "Bullet" lake, @ 11,900' elev.

incipient sericitization along plagioclase grain boundaries to wholesale conversion of Pl, Bt and Hb to sericite, phengite and Ep along small (<1 mm) quartz veins.

Suite RM2, collected ~75 m northeast from RM1, was taken from one 2.5 kg specimen (15 cm maximum dimension) of Fsp-Ms schist. Chips cut from the sides and corners of the large block produced seven samples for isotopic analyses. Composed of Q + Ms + Kfs + Pl + minor Bt + opaques + tr. Gt, its texture is dominated by a prominent mm-scale spaced cleavage. In thin section, relict Ms aligned in an early foliation can rarely be seen between the spaced Ms folia that define the most prominent foliation. Biotite imperfectly mimics Ms texture. Alteration is confined to minor sericitization of feldspars along grain boundaries and twin planes and partial conversion (<30%) of biotite to clay.

Suite RM3, collected at the base of the northwest wall of the canyon of the Rio Mora 0.6 km above its confluence with the creek draining Bordo del Medio, consists of seven samples of a fine-grained medium-gray Bt-Pl schist. This site lies within 2–3 m of the thrust fault which carried the Pecos complex (Pecos terrane) northward and over the Hondo Group (Truchas terrane) (Grambling et al., 1988). All samples were taken from a prominently foliated slab 1 m thick by 5 m by 7 m parallel to the foliation. Composed of Pl ± Bt + Q + opaques + minor Ap + tr. Gt, these samples appear weakly foliated in hand specimen and thin section. Alteration is confined to minor conversion of Pl to sericite, slight replacement of Bt by Chl, and rare rimming of opaques by thin fringes of secondary hematite. Indistinct stringers of Q and Bt are suggestive of a spaced cleavage, implying at least two episodes of foliation development.

Suite RV1, collected on the west bank of the Rio Valdez 150 m north of the contact between intrusive granitic rocks and amphibolites of the Pecos complex, consists of six samples collected within a 3 m radius. These rocks are medium to coarse-grained amphibolites of generally massive texture, composed of Hb + Q + Pl + opaques. Hornblende needles exhibit varying degrees of alignment, sometimes imparting a faint lineation or foliation. Infrequently, Pl exhibits partially developed oscillatory zoning, presumably a relict igneous feature. Alteration is variable, ranging from slight replacement of Pl by fine-grained muscovite to nearly complete sericitization of plagioclase and minor replacement of hornblende by chlorite, clay and epidote. Epidote also occurs in nearly pristine samples lacking other signs of alteration.

Truchas terrane

The Truchas amphibolite suite is a composite of samples collected at three sites: TR39 (n = 2), TR40 (n = 2) and TR45 (n = 4). Each sample comes from a different amphibolite layer in the intercalated amphibolite-quartzite sequence to the north of Truchas Peak. See Figure 3 and Table 1 for approximate field relations. This suite exhibits large mineralogic variations between samples, presumably the result of significant variations in initial bulk composition. Samples at one mineralogic extreme contain long (2 cm) parallel laths of golden-brown pseudomorphs of clay(?) after amphibolite in a fine-grained strongly lineated matrix of fresh hornblende and leucocratic minerals, whereas samples at the other extreme are weakly foliated to massive and/or contain significant amounts of coarse-grained chlorite (up to 4 mm) in a medium-grained matrix of hornblende and plagioclase. The dominant mineral assemblage is Hb + Pl + Q + Chl ± Bt + opaques. Several samples are cut by thin veins of Chl, Ep or Pl. Rarely, veins exhibit reaction selvages, with opaque minerals converted to rutile. Chlorite occurs in randomly oriented polycrystalline knots and as a replacement of biotite. Alteration is uncommon but is observed as minor sericitization of Pl and as replacement of porphyroblastic Hb needles by brown clay.

Suite TR41 consists of eight samples collected on a 40 m traverse across continuous outcrop of white fine-grained Q-Ms schist located in the topographic saddle due north of Truchas Peak. A strongly differentiated cleavage, consisting of 0.5 mm thick layers of muscovite spaced approximately 1 cm apart, cuts a fainter penetrative cleavage at an angle of 30° to 40°. Mineralogy is nearly invariant, consisting of Q + Ms + Pl + Kfs + trace Gt. Alteration is confined to minor sericitization of Pl in most sections, rarely coarsening to recognizable Ms flakes (e.g., TR41A). Other than Ms, pure mineral separates from TR41-5 could not be obtained, although density discrimination provided a degree of separation. The ratio of Pl:Kfs:Ms in the heavy fraction (H) was 5:3:3, the heavy intermediate fraction (HM) 20:15:0, the light intermediate fraction (LM) 60:25:0 and the light fraction (L) 10:85:1. Quartz was a dilutent in all fractions (89%, 65%, 15% and 5% in H, HM, LM and L, respectively).

The Rinconada schist suite, collected on the southern flank of Pecos Baldy at the top of the cliff overlooking "Bullet" lake (informally named by Grambling, personal commun.), consists of nine chips cut from PB31 and one from PB32. These samples are typified by porphyroblasts of Bt, Gt and Stl (all ~2 mm dia.) in a fine-grained matrix of Ms + Q + Kfs(?). Quartz-rich 0.5-cm layers define primary bedding. An early foliation is parallel to bedding, whereas a second foliation forms a closely spaced (<0.5 mm) differentiated cleavage that bends around the porphyroblasts, giving the rock a knotty appearance. Porphyroblasts are commonly sieve-textured, with inclusion trails oriented at an angle to the dominant second-stage foliation. Signs of late-stage alteration include clots of Ep + Chl (replacing Pl?); Kfs(?) contains abundant inclusions of randomly oriented Ms flakes that may represent sericitization and subsequent annealing.

DATA AND RESULTS

Rb-Sr isochrons

Complete Rb-Sr analytical results are presented in Tables 2 and 3. Within each terrane, isochrons are discussed in chronological order, beginning with the oldest. Regression errors are given at the 95%

TABLE 2. Analytical data for samples from the Pecos terrane. s.d. = standard deviation, r = error correlation coefficient.

	< raw >					< blank subtracted >		
Sample ID	Weight (mg)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	s.d.	$^{87}Sr/^{86}Sr$	s.d.	r
Amphibolite from lower Rio Mora								
RM1-1	300.92	6.06	282.88	0.065	0.000	0.706628	0.000182	0.000
RM1-2	298.87	6.94	325.60	0.064	0.000	0.706249	0.000182	0.000
RM1-3	302.72	16.71	193.66	0.262	0.001	0.711230	0.000214	0.000
RM1-4	300.05	4.14	303.17	0.041	0.000	0.706188	0.000180	0.000
Amphibolite from Rio Valdez								
RV1-1	305.34	8.03	222.59	0.109	0.001	0.706058	0.000187	0.000
RV1-2	204.11	5.02	233.69	0.065	0.000	0.705514	0.000182	0.000
RV1-3	332.97	9.03	288.94	0.095	0.000	0.706199	0.000185	0.000
RV1-4	300.42	9.55	219.30	0.132	0.001	0.707428	0.000190	0.000
RV1-5	299.62	2.80	244.12	0.035	0.000	0.704578	0.000179	0.000
RV1-6	302.81	25.62	262.49	0.296	0.001	0.710690	0.000223	0.000
Biotite-plagioclase schist from the Pecos-Truchas suture, Rio Mora								
RM3-1	303.57	54.14	425.31	0.386	0.002	0.711570	0.000262	0.000
RM3-2	304.30	56.41	482.95	0.354	0.002	0.711000	0.000245	0.000
RM3-3	296.28	59.58	797.82	0.226	0.001	0.708090	0.000206	0.000
RM3-4	317.64	50.48	372.95	0.411	0.002	0.712040	0.000278	0.000
RM3-5	301.58	65.82	378.67	0.527	0.003	0.714371	0.000497	0.004
RM3-6	300.70	76.52	319.44	0.727	0.004	0.717696	0.000471	-0.002
RM3-7	300.06	84.39	299.44	0.856	0.004	0.720802	0.000345	-0.001
Feldspar-muscovite schist from lower Rio Mora								
RM2A	311.10	75.88	113.93	2.029	0.010	0.751157	0.000257	0.000
RM2B	305.85	94.28	93.55	3.076	0.015	0.771171	0.000253	0.000
RM2C	298.56	89.01	113.46	2.391	0.012	0.756542	0.000254	0.000
RM2D	300.90	85.26	117.32	2.215	0.011	0.754660	0.000255	0.000
RM2E	300.09	84.90	114.56	2.259	0.011	0.757192	0.000255	0.000
RM2F	299.93	94.11	118.28	2.426	0.012	0.760544	0.000255	0.000
RM2G	300.45	79.57	116.53	2.080	0.010	0.752869	0.000256	0.000
RM2D Pl	312.99	7.36	131.01	0.170	0.001	0.717583	0.000198	0.000
RM2D Kfs	306.41	111.61	263.83	1.287	0.006	0.737458	0.000275	0.000
RM2D Ms	500.86	307.51	36.33	26.901	0.135	1.208138	0.000350	0.000
RM2D Bt	299.94	331.76	28.22	38.109	0.191	1.414574	0.000404	0.000
RM2D Bt	83.81	346.55	23.57	48.993	0.248	1.623232	0.000486	0.001
RM2D Bt	84.34	351.60	23.18	50.672	0.256	1.651275	0.000495	0.001

TABLE 3. Analytical data for samples from the Truchas terrane. s.d. = standard deviation, r = error correlation coefficient.

	< raw >			< blank subtracted >				
Sample ID	Weight (mg)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	s.d.	$^{87}Sr/^{86}Sr$	s.d.	r
Amphibolite from Truchas Peak								
TR39-1	302.40	1.53	258.07	0.018	0.000	0.705238	0.000177	0.000
TR39-3	302.54	1.81	304.34	0.018	0.000	0.705338	0.000178	0.000
TR40-1	301.16	60.48	605.98	0.303	0.002	0.712000	0.000226	0.000
TR40-2	302.11	49.58	762.50	0.197	0.001	0.709940	0.000201	0.000
TR45-2	309.54	1.00	267.27	0.011	0.000	0.704878	0.000177	0.000
TR45-4	301.37	4.75	231.78	0.062	0.000	0.706388	0.000182	0.000
TR45-5	299.76	1.30	255.68	0.015	0.000	0.705028	0.000177	0.000
TR45-6	301.29	2.55	241.46	0.032	0.000	0.705528	0.000179	0.000
TR45-9	299.87	3.57	306.89	0.035	0.000	0.705368	0.000179	0.000
Quartz-muscovite schist from Truchas Peak								
TR41-1	300.38	197.92	35.35	17.604	0.088	1.078095	0.000320	0.000
TR41-2	300.78	148.57	26.94	17.367	0.087	1.088177	0.000324	0.000
TR41-3	302.33	172.83	25.55	21.450	0.108	1.163311	0.000342	0.000
TR41-4	301.34	176.49	26.94	20.779	0.104	1.167605	0.000343	0.000
TR41-5	300.57	186.18	28.51	20.675	0.104	1.149120	0.000338	0.000
TR41-6	300.50	148.56	17.30	27.552	0.138	1.278048	0.000373	0.000
TR41-7	254.50	168.64	16.07	34.092	0.171	1.407303	0.000409	0.000
TR41A	300.97	137.32	7.49	62.667	0.317	1.941038	0.000574	0.001
TR41-5 H	312.73	206.91	39.28	16.561	0.083	1.080625	0.000321	0.000
TR41-5 HM	301.03	18.66	13.79	4.179	0.021	0.850357	0.000275	0.000
TR41-5 LM	304.59	46.58	37.34	3.829	0.019	0.819522	0.000264	0.000
TR41-5 L	300.00	210.28	83.74	7.768	0.039	0.914467	0.000281	0.000
TR41-5 Ms	301.20	466.72	11.55	159.618	0.804	3.852507	0.001085	0.001
Rinconada schist (pelitic) from Pecos Baldy								
PB31-1A	255.50	105.27	80.17	4.015	0.020	0.787285	0.000254	0.000
PB31-1B	251.00	89.41	113.34	2.405	0.012	0.757199	0.000254	0.000
PB31-1C	251.60	96.84	53.92	5.509	0.028	0.815232	0.000259	0.000
PB31-2A	251.20	113.96	88.35	3.944	0.020	0.787237	0.000254	0.000
PB31-2B	250.70	79.12	162.62	1.481	0.007	0.742456	0.000267	0.000
PB31-2C	251.20	92.90	55.98	5.086	0.025	0.806653	0.000258	0.000
PB31-3A	262.70	105.44	80.47	4.007	0.020	0.787354	0.000254	0.000
PB31-3B	255.30	81.86	146.62	1.700	0.009	0.745917	0.000262	0.000
PB31-3C	174.85	95.71	55.99	5.245	0.026	0.809226	0.000259	0.000
PB32	249.80	147.88	83.18	5.449	0.027	0.812012	0.000258	0.000
PB31-3C Ms	71.88	15.10	124.42	3.695	0.019	0.790181	0.000258	0.000
PB31-3C Bt	85.02	567.75	13.30	169.309	0.863	3.705063	0.001227	0.005
PB31-3C Bt	169.40	553.85	14.05	152.303	0.769	3.504971	0.001022	0.001
PB31-3C Bt	163.30	553.81	15.34	133.647	0.674	2.946175	0.000845	0.001

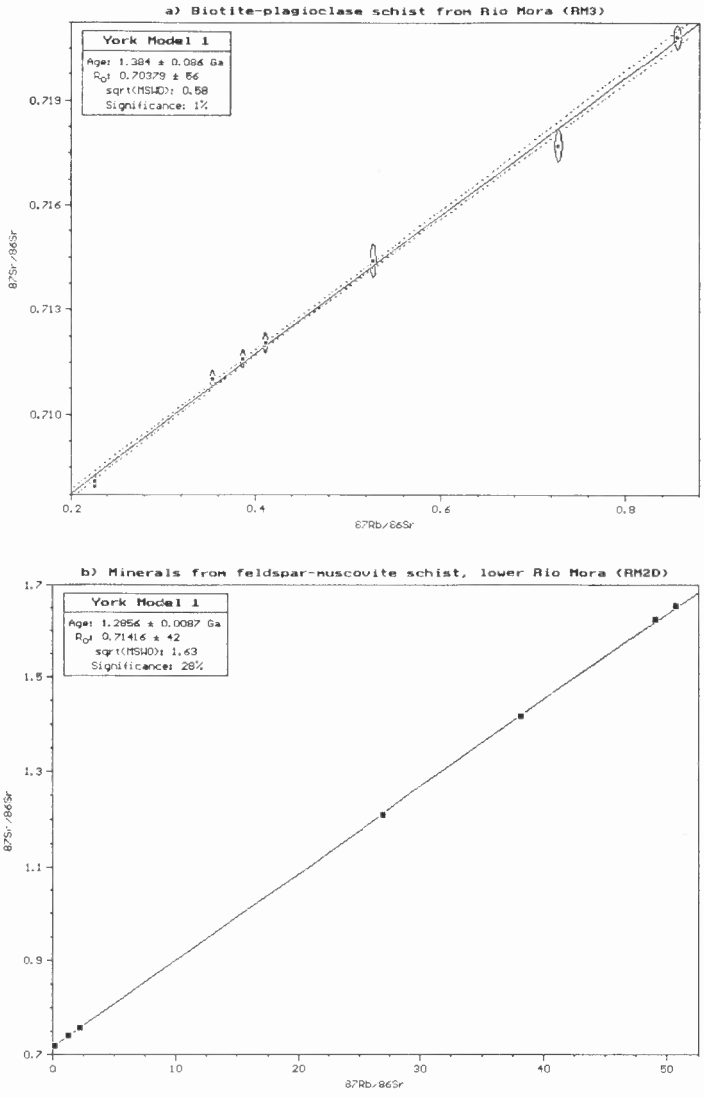


FIGURE 4. Two isochrons from the Pecos greenstone belt. a, Bt-Pl schist from the Vadito-Ortega contact, Rio Mora (suite RM3). b, Minerals (Pl, Kfs, Ms and three Bt) and whole-rock from Fsp-Ms schist, lower Rio Mora (suite RM2D).

confidence level, ages are summarized in Table 4, and the four isochrons of most consequence, two from each terrane, are plotted in Figs. 4 and 5.

Pecos terrane

The two oldest ages from the Pecos terrane are from amphibolite lithologies, with model 1 ages of 1640 ± 230 Ma (RM1, n = 4) and 1630 ± 250 Ma (RV1, n = 6), with *rMSWD* = 1.9 and 2.5, *significance* = 48% and 6% respectively. With the precision levels of this study, analytical scatter has an acceptable probability of accounting for most of the variation seen in the RM1 data set, and has a non-zero probability of accounting for the variation in the RV1 set as well. The large errors associated with these ages are a consequence of the restricted range of $^{87}Rb/^{86}Sr$ ratios exhibited by these samples (<0.3). Initial $^{87}Sr/^{86}Sr$ ratios of 0.70503 ± 43 (RM1) versus 0.70390 ± 49 (RV1) differ significantly, possibly implying different sources for the protoliths of these rocks. Perturbations to the Rb-Sr systematics of these basic metavolcanics as a consequence of regional metamorphism some 300 Ma after emplacement are not resolvable at the level of analytical precision attained in this study.

The seven-point isochron from RM3 Bt-Pl schist (Fig. 4a) is well-behaved, giving a model 1 age of 1384 ± 86 Ma, intercept of 0.70379 ± 56, and *rMSWD* = 0.58. The good fit of this isochron is consistent with the nearly pristine quality of the samples, which show only slight amounts of sericite and secondary chlorite. In fact, a fit this good can be expected only 1% of the time based on the estimated analytical precisions of this study. As this isochron is the only unusually tight fit among those of this study, estimated analytical precisions are accepted as valid, and this tight fit is attributed to random chance. Although initial $^{87}Sr/^{86}Sr$ of RM3 is essentially identical with that of RV1, its present mineralogy contains Bt rather than Hb as the dominant mafic phase. The Bt is present possibly as a consequence of pre-metamorphic hydrothermal

TABLE 4. York regression results. See Methods section for explanation of Model, sqrt MSWD, Significance, and Geologic Scatter columns.

Suite	n	Age (Ma)	Intercept	Model	sqrt MSWD	Significance	Geol. Scatter
Pecos Terrane							
RM1 amphibolite	4	1640 ± 230	0.70503 ± 0.00043	1	1.90	0.48	
RV1 amphibolite	6	1630 ± 250	0.70390 ± 0.00049	1	2.75	0.06	
RM3 Bt-Pl schist	7	1384 ± 86	0.70379 ± 0.00056	1	0.58	0.01	
RM2 Fsp-Ms schist	7	1310 ± 260	0.7136 ± 0.0089	3			0.0012
RM2D Fsp-Ms sch. minerals	7	1285.6 ± 8.7	0.71416 ± 0.00042	1	1.63	0.28	
Truchas Terrane							
Truchas amph. (TR39, 40 & 45)	9	1730 ± 110	0.70473 ± 0.00017	1	1.05	0.94	
TR41 Q-Ms schist	8	1319 ± 42	0.759 ± 0.018	3			0.0086
TR41-5 Q-Ms sch. minerals	6	1352 ± 24	0.758 ± 0.014	3			0.010
PB31 Rinconada Formation	10	1253 ± 28	0.715 ± 0.016	3			0.0007
PB31-3C Rincon. Fm. minerals	5	1230 ± 130	0.71 ± 0.22	3			0.094

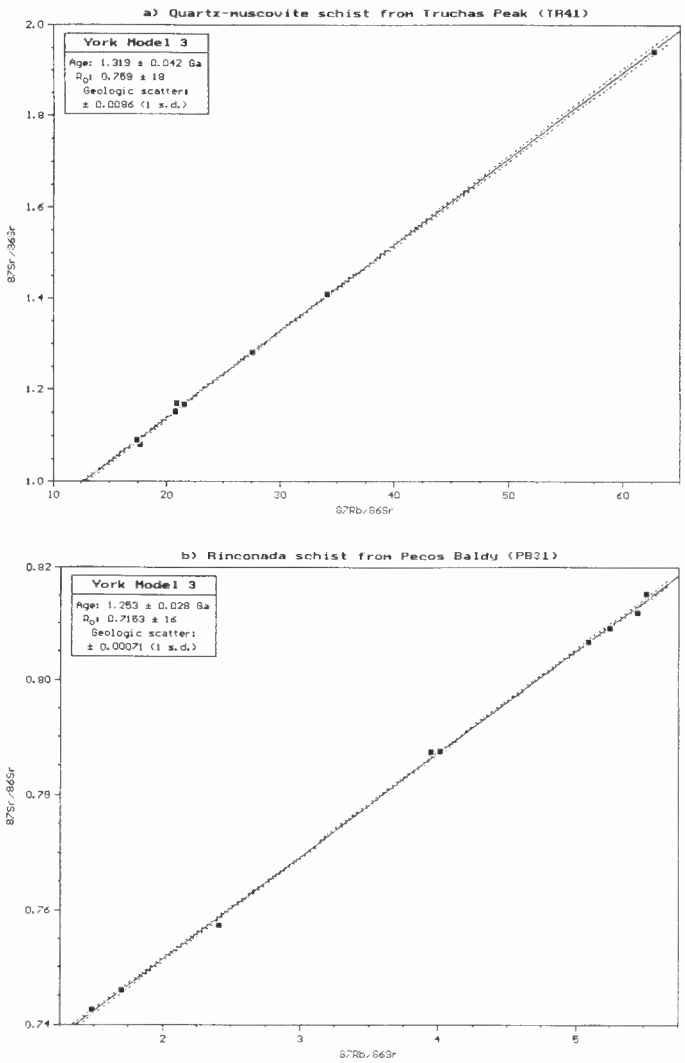


FIGURE 5. Two isochrons from the Truchas terrane. a, Q-Ms schist from Truchas Peak (suite TR41). b, Rinconada (pelitic) schist from Pecos Baldy (suite PB31 and 32).

alteration or metasomatism, or possibly because this rock may have had a non-volcanic protolith.

A model 3 and a model 1 isochron, each with seven points, were obtained from RM2 Fsp-Ms schist. This sample gave a poor whole-rock isochron (1310 ± 260 Ma, 0.7136 ± 89, *geologic scatter* = 0.0012) and a much better constrained mineral-separate isochron from RM2D (1285.6 ± 8.7 Ma, 0.71416 ± 42, *rMSWD* = 1.63, *significance* = 28%) as shown in Figure 4b. Geologic scatter in the whole-rock isochron may be related to incomplete resetting during the event dated by the mineral-separates. Scatter in the mineral-separate isochron may reflect only analytical scatter. The small error of the mineral-separate isochron is mainly a consequence of the large span of $^{87}Rb/^{86}Sr$ (nearly 50) in comparison to the whole-rocks (slightly more than 1) rather than the *geologic scatter* of the whole-rock isochron.

Truchas terrane

Three sets of samples from the Truchas amphibolite suite—TR39, TR40 and TR45. Two of the sets (TR39 and TR45) sample different parts of the intercalated quartzite-amphibolite near the axis of a syncline centered on Truchas Peak, and the remaining set consists of two samples from a nearby mafic gneiss. All basaltic protoliths may have had similar initial $^{87}Sr/^{86}Sr$ if they shared a common igneous source; they all plot on the same model 1 isochron (1730 ± 110 Ma, 0.70473 ± 17, *rMSWD* = 1.05, *significance* = 94%). The large uncertainty in age is attributable to the restricted range of $^{87}Rb/^{86}Sr$ (0.011 to 0.303). As with amphibolites from the Pecos terrane, perturbations to Rb-Sr systematics as a consequence of regional metamorphism are not resolvable at the level of analytical precision attained in this study. In addition to regional metamorphism, some of these samples have suffered varying degrees of alteration (late-stage Chl, alteration of porphyroblastic Hb to clay), but these have not had any resolvable effects on Rb-Sr systematics either.

This composite isochron is meaningful only if the three sample sets are consanguineous or fortuitously had the same initial $^{87}Sr/^{86}Sr$. Sets TR39 and TR45 are almost certainly coeval as they were collected from the same stratigraphic unit, but kinship to TR40 may be questionable since it is stratigraphically distinct, occurring somewhat lower in the section. Indeed, the fact that the combined suites yield a reasonable isochron is a strong argument in favor of a close genetic relation among the three sets.

Both a whole-rock (Fig. 5a) and a mineral separate isochron were obtained from TR41 Q-Ms schist. The model 3 whole-rock isochron (n = 8, 1319 ± 42 Ma, 0.759 ± 18, *geologic scatter* = 0.0086) and mineral separate isochron (n = 6, 1352 ± 24 Ma, 0.758 ± 14, *geologic scatter* = 0.010) do not differ significantly in age or initial $^{87}Sr/^{86}Sr$, and both contain large and similar amounts of unexplained scatter. Petrographic examination reveals only pristine samples, so either analytical precisions have been underestimated for samples with high $^{87}Sr/^{86}Sr$ (up to 3.85 for Ms here), or *geologic scatter* may be quite real, arising either as a consequence of varying closure temperatures for the various mineral phases during cooling from regional metamorphic conditions or because of multiple heating events.

The youngest Rb-Sr ages from the Truchas terrane obtained in this study are from the pelitic Rinconada Formation near Pecos Baldy, a few km south of the sampling sites at Truchas Peak. As is true for the TR41 Q-Ms schist, the model 3 whole-rock isochron (1253 ± 28 Ma, 0.715 ± 16, *geologic scatter* = .0007), presented in Figure 5b, and mineral-separate isochron (1232 ± 130 Ma, 0.71 ± 22, *geologic scatter* = 0.094) are identical within error limits, but in this instance the mineral-separate isochron requires an order of magnitude more *geologic scatter* to satisfy model 3 conditions. The whole-rock isochron requires only a small amount of geologic scatter, approximately the same as required by the Fsp-Ms schist (RM2) of the Pecos terrane and an order of magnitude less than required by the Q-Ms schist of Truchas terrane (TR41). As both normal (PB31-XA,C) and Q-rich (PB31-XB) layers were analyzed and found to lie on the same model 3 isochron, Sr mobility during metamorphism apparently was great enough to completely homogenize Sr isotopes across the quartzose layers.

The analyzed mineral separates include a Ms fraction and three aliquots of the same Bt fraction; the Ms point falls very close to the whole-rock point, not surprising for a pelitic schist, but the Bt points are quite scattered, indicative either of sample inhomogeneity or analytical difficulties. Thus, this isochron is of doubtful significance.

K-Ar dates

Two K-Ar dates were obtained, one from each of the terranes. Muscovite (sample RM2D) from the Pecos terrane gave an age of 1320 ± 43 Ma (1σ), and Ms (sample TR41-5) from the Truchas terrane gave an age of 1266 ± 42 Ma (1σ). Details of the K and Ar analyses are given in Ward (1986). As the error ranges of these two dates overlap significantly, they could represent a single event which took place at an age of 1293 ± 40 Ma (1σ).

DISCUSSION

Implications for regional chronology

Ages from both the Pecos and Truchas terranes are bimodally distributed, with older ages falling near 1670 Ma and younger ones near 1300 Ma. All pairings of ages between the two groups are statistically distinct at the 95% confidence level. Usually it is assumed that whole-rock ages will see through the "metamorphic veil" (Faure, 1986) to yield formational ages, and this may indeed be the case with the older isochrons. All three of these are model 1 isochrons, with levels of

observed scatter explainable by analytical precision, and are consistent with U-Pb zircon ages which constrain primary igneous activity to the period 1650 to 1765 Ma.

The younger ages, mostly model 3 isochrons, are rather scattered, ranging from 1384 to 1232 Ma. The more precise ages can be statistically grouped in 3 sets, all distinct at the 95% confidence level: (1) 1384, 1352 and 1319 Ma; (2) 1285.6 Ma; and (3) 1253 Ma. These dates, clearly much younger than formational ages, are somehow related to younger thermal events. The youngest ages are consistent with K-Ar ages on micas from these and other Proterozoic terranes in northern New Mexico (cf. Brookins, 1974; Brookins and Shafiqullah, 1975; Gresens, 1975; Brookins et al., 1977) and with a Ms $^{40}Ar/^{39}Ar$ age (Grambling and Dallmeyer, 1990), all of which may be interpreted to reflect the timing of a late-stage thermal event (Grambling and Dallmeyer, 1990). The age of regional amphibolite-facies metamorphism, crucial to interpreting the remaining ages, is constrained by $^{40}Ar/^{39}Ar$ ages on Hb from the Cimarron, Sandia and Manzano ranges (Grambling and Dallmeyer, 1990; Thompson et al., in prep.) to be within the range 1400–1440 Ma; the blocking temperature for Ar diffusion is near 500°C (Harrison, 1981), very close to peak *P-T* conditions recorded by metamorphic mineral assemblages in both the Pecos and Truchas terranes as well as the Sandia, Manzano and parts of the Cimarron ranges. Thus, the remainder of the young ages of this study, which lie between 1400 Ma and 1300 Ma, are probably the result of complete metamorphic resetting to ~1400 Ma coupled with variable resetting superimposed during one or more later thermal events; a likely age for one of these events is ~1285 Ma, as recorded by the minerals of RM2D.

Effects of metamorphism on Rb-Sr systematics

Lithology appears to exert an overwhelming control on the response of Rb-Sr whole-rock systematics to metamorphism. Several responses are apparent from this study: (1) lithologies which express a differentiated cleavage are thoroughly reset by metamorphism; (2) lithologies dominated by micas are subject to at least partial resetting by subsequent heating events; and (3) lithologies lacking a differentiated cleavage respond only weakly, if at all, to metamorphism in spite of recrystallization and even micro- and mesoscopic transposition of layering.

The metamorphic development of a differentiated or crenulated cleavage implies significant dissolution, mass transport and recrystallization on a scale of millimeters to centimeters (Gray and Durney, 1979; Hanmer, 1979; Bell et al., 1986). Homogenization of Sr isotopes should occur on a similar scale, and may occur on a larger scale as well as fluids associated with progressive dehydration move through the rock. To produce reset model 1 whole-rock isochrons, Sr isotopes must be well mixed throughout the *characteristic volume,* a volume large enough to thoroughly average any pre-metamorphic "lumpiness" in $^{87}Sr/^{86}Sr$ so that resultant $^{87}Sr/^{86}Sr$ is uniform throughout the unit. Failure to achieve homogenization at this level (for whole rocks) or at the level of differentiation processes (for mineral separates) will show up as *geologic scatter* on a model 3 isochron.

Although all micaceous rocks of this study exhibit differentiated cleavages, their sensitivity to resetting by subsequent thermal events appears to be related to the quantity and mineralogy of mica present. Biotite-Pl schist (RM3), which yields the oldest age and thus appears to have been least affected by young thermal events, contains only a moderate proportion of Bt (~20%), whereas the pelitic Rinconada Q-Ms schist (PB31) was nearly completely reset and is dominated by Ms. Muscovite with high Rb/Sr completely controls the Rb-Sr systematics of PB31 (a model 3 isochron), but Bt with comparatively low Rb/Sr has a much smaller effect on RM3 (a marginal model 1 isochron).

Thermal resetting of Rb-Sr systematics of micas was apparently accomplished under nearly dry conditions, as these rocks contain scant evidence of alteration after peak metamorphic conditions. Thermal resetting of Rb-Sr systematics is easily understood—daughter Ar can readily diffuse out of the mica structure at elevated temperatures. But what about daughter Sr? It will occur as Sr^{2+} in an M^{+} site, but should not have to diffuse far to find a more accommodating location. To reset a whole-rock isochron, though, diffusion would have to occur throughout the *characteristic volume*. Neither the size of the *characteristic volume* nor the mechanism of thermal resetting at moderate temperatures is clear; resolution of these questions may have important implications for solid-state diffusion of other elements under similar conditions.

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The aptly named Heartbreak Mill, Red River District. Courtesy of Museum of New Mexico, neg. no. 5273.