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Silurian plutonism in the Trinity terrane (Neoproterozoic and Ordovician), Klamath Mountains, California, United States

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Abstract. New data indicate that the Trinity terrane of northern California is a polygenetic composite terrane rather than a single slice of oceanic lithosphere. We suggest approximately one third of the Trinity terrane consists of Silurian intrusive rocks that represent the roots of a previously unrecognized Silurian magmatic arc. Crosscutting relations and U-Pb zircon isotopic data document at least one early Paleozoic deformation in the Trinity terrane of northern California. A ductile shear zone between Neoproterozoic metagabbro and Ordovician(?) harzburgite is intruded by the Upper Silurian China Mountain pluton. This evidence indicates a major early Paleozoic shear zone formed in the eastern Klamath Mountains after the Middle Ordovician but prior to Late Silurian plutonism.

Introduction and Geologic Setting

Lower Paleozoic eugeoclinal rocks crop out discontinuously along the North American Cordilleran margin from northern Mexico to western Canada. In California, a relatively continuous segment of this belt extends from the Klamath Mountains southward through the Sierra Nevada to the Garlock fault [Schweickert, 1981]. The Klamath Mountains consist of arcuate west facing, east dipping lithotectonic belts that young to the west and record multiple episodes of Ordovician to Jurassic convergent margin tectonism [Irwin, 1989]. We follow the classification of terranes used by Silberling et al. [1992]. The Eastern Klamath belt comprises the Trinity, Yreka, and Eastern Klamath terranes, which contain the oldest rocks in northern California (Figure 1). The Trinity terrane is an extensive exposure of Neoproterozoic and lower Paleozoic intrusive rocks that constitutes the basement of the Yreka and Eastern Klamath terranes [Irwin, 1977; Lindsley-Griffin, 1991]. The Trinity terrane comprises harzburgite, lherzolite, plagioclase lherzolite, dunite, serpentinite, gabbro, and plagiogranite [Lindsley-Griffin, 1991].

For many years, the Trinity terrane was believed to be principally Ordovician in age on the basis of sparse geochronological data. Previous workers recognized crosscutting relationships between some intrusive bodies, but their interpretations were limited by a lack of precise isotopic ages [Lindsley-Griffin, 1977; Lindsley-Griffin, 1982; Quick, 1981a, b; Schwindinger and Anderson, 1987]. The only estimate of the age of ultramafic rock in the Trinity terrane is a Sm-Nd isochron of 472 ±32 Ma for plagioclase lherzolite [Jacobsen et al., 1984]. One gabbro intrusion yielded K-Ar hornblende ages of 426 and 447 Ma [Lanphere et al., 1968] (434 and 455 Ma, respectively, using the newer International Union of Geological Sciences (IUGS) decay constants of Steiger and Jäger [1977]). Gabbro and plagiogranite in a structurally complex zone between melange of the Yreka terrane and ultramafic rocks of the Trinity terrane also yield Ordovician U-Pb ages ranging from 440 to 475 Ma [Hopson and Mattinson, 1973; Wallin et al., 1988]. These rocks are tentatively included in the Trinity terrane but could be blocks in melange of the Yreka terrane [Wallin, 1990; Lindsley-Griffin et al., 1991]. Wallin et al. [1988] demonstrated that plagiogranitic rocks along the northwestern margin of the Trinity terrane crystallized at about 565 Ma, which is Neoproterozoic [Bowring et al., 1993] and thus unrelated genetically to Ordovician ultramafic rocks of the Trinity terrane. The Neoproterozoic rocks appear to constitute a small crustal fragment along the northwestern margin of the Trinity terrane, and they also occur as tectonic blocks in melange of the Yreka terrane [Wallin et al., 1988; Wallin, 1990]. Below we present additional isotopic evidence that underscores the polygenetic nature of the Trinity terrane emphasized previously by Jacobsen et al. [1984] and Wallin et al. [1988].

The juxtaposition of the Neoproterozoic rocks with ultramafic rock of the Trinity terrane appears to have been tectonic rather than intrusive because only faulted contacts are observed. In the Trinity terrane, northwest of China Mountain, Ordovician(?) serpentinized harzburgite with a mantle tectonite fabric is faulted against a large body of strongly foliated metagabbro (Figure 2). This 0.5-km-wide shear zone, herein termed the China Mountain Shear Zone, marks a significant change in the metamorphic grade, structural style, and age of rocks in the Trinity terrane. Mafic and intermediate metaplutonic rocks west of the shear zone appear to be mostly Neoproterozoic [Wallin et al., 1988], whereas ultramafic rocks to the east are at least in part Ordovician [Jacobsen et al., 1984]. The age of ultramafic rock west of the shear zone is unknown and is shown provisionally as Ordovician (Figure 2); the significance of these exposures is discussed further below. The China Mountain Shear Zone contains anastomosing phacoids of foliated metagabbro and serpentinized harzburgite with a vertical ductile fabric and is intruded by undeformed pegmatitic gabbro of the China Mountain pluton (Figure 2).

Pegmatitic gabbro of the China Mountain pluton comprises subequal amounts of plagioclase feldspar and pyroxene, with subordinate interstitial hornblende; its texture varies locally from pegmatitic to fine-grained [Lindsley-Griffin, 1991]. This texturally distinctive gabbro is similar to that described from elsewhere in the Trinity terrane by Schwindinger and Anderson [1987]. We collected samples of both the metagabbro and the younger pegmatitic gabbro for geochronological study to place limits on the timing of this early Paleozoic deformation.

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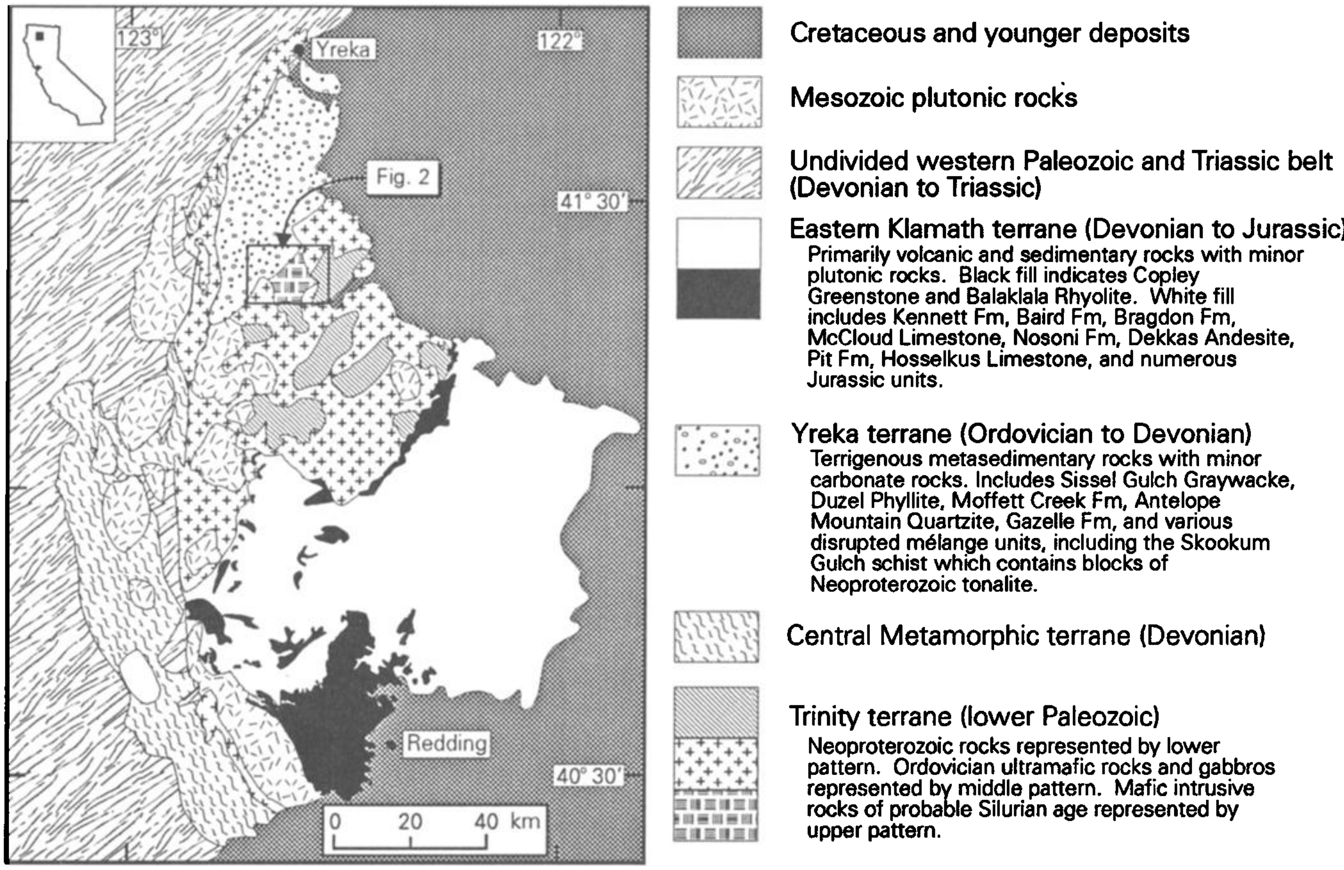

Figure 1. Generalized geologic map of the eastern Klamath Mountains.

U-Pb Geochronology

Zircons from the metagabbro and pegmatitic gabbro were spiked with mixed Pb/U tracers and analyzed using methods modified after Krogh [1973]. Forty kilograms of the metagabbro yielded 7 mg of slightly metamict, pink, subhedral zircon. Five fractions separated on the basis of magnetic susceptibility yielded scattered, slightly discordant $^{207}Pb/^{206}Pb$ ages ranging from 556 to 579 Ma [Figure 3, Table 1]. It is uncertain whether the scatter is the result of a slight disturbance of the isotopic systematics by metamorphism or whether there is a minor component of inherited Precambrian zircon. This latter possibility is consistent with the occurrence of xenocrystic Precambrian zircon in a Neoproterozoic tonalite nearby in the Yreka terrane [Wallin, 1990]. In either case, we interpret the metagabbro to be coeval with the suite of Neoproterozoic (~565 Ma) plagiogranites [Wallin et al., 1988].

Forty kilograms of pegmatitic hornblende gabbro from the China Mountain pluton yielded 6 mg of colorless, euhedral, inclusion-free zircon with brilliant crystal faces. The zircon population was separated into two fractions on the basis of magnetic susceptibility. The relatively magnetic fraction yielded a $^{207}Pb/^{206}Pb$ age of 415 ±2 Ma that is concordant within analytical uncertainty. The relatively nonmagnetic fraction exhibits slight discordance but yields a similar $^{207}Pb/^{206}Pb$ age (Figure 4, Table 1). Allowing for the very minor discordance of both fractions, a reasonable estimate of the crystallization age is 415 ±3 Ma.

Nd Isotopic Signature of Pegmatitic Gabbro

Pegmatitic gabbro of the China Mountain pluton yields an $\varepsilon_{Nd(415\ Ma)}$ of +7.3 and a depleted mantle model age of 414 Ma (Table 2). Similar initial Nd isotopic compositions were reported from the Trinity terrane for dikes of undeformed microgabbro (+6.6 to +6.9) and pyroxenite (+7.3) [Jacobsen et al., 1984]. The remarkable agreement between the U-Pb crystallization age and the Sm-Nd model age for the pegmatitic gabbro supports derivation of the gabbro from depleted mantle during the Silurian with little or no involvement of older crust or subsequent disturbance of the isotopic systematics.

Tectonic Implications

Timing of Geologic Events

The metagabbro clearly is related spatially and temporally to Neoproterozoic plagiogranites that occur along the northwestern margin of the Trinity terrane and tonalites that occur as blocks in melange of the Yreka terrane [Wallin et al., 1988]. The Neoproterozoic age of the metagabbro indicates that the Neoproterozoic suite is polylithologic and more areally extensive than was recognized previously (Figures 1 and 2).

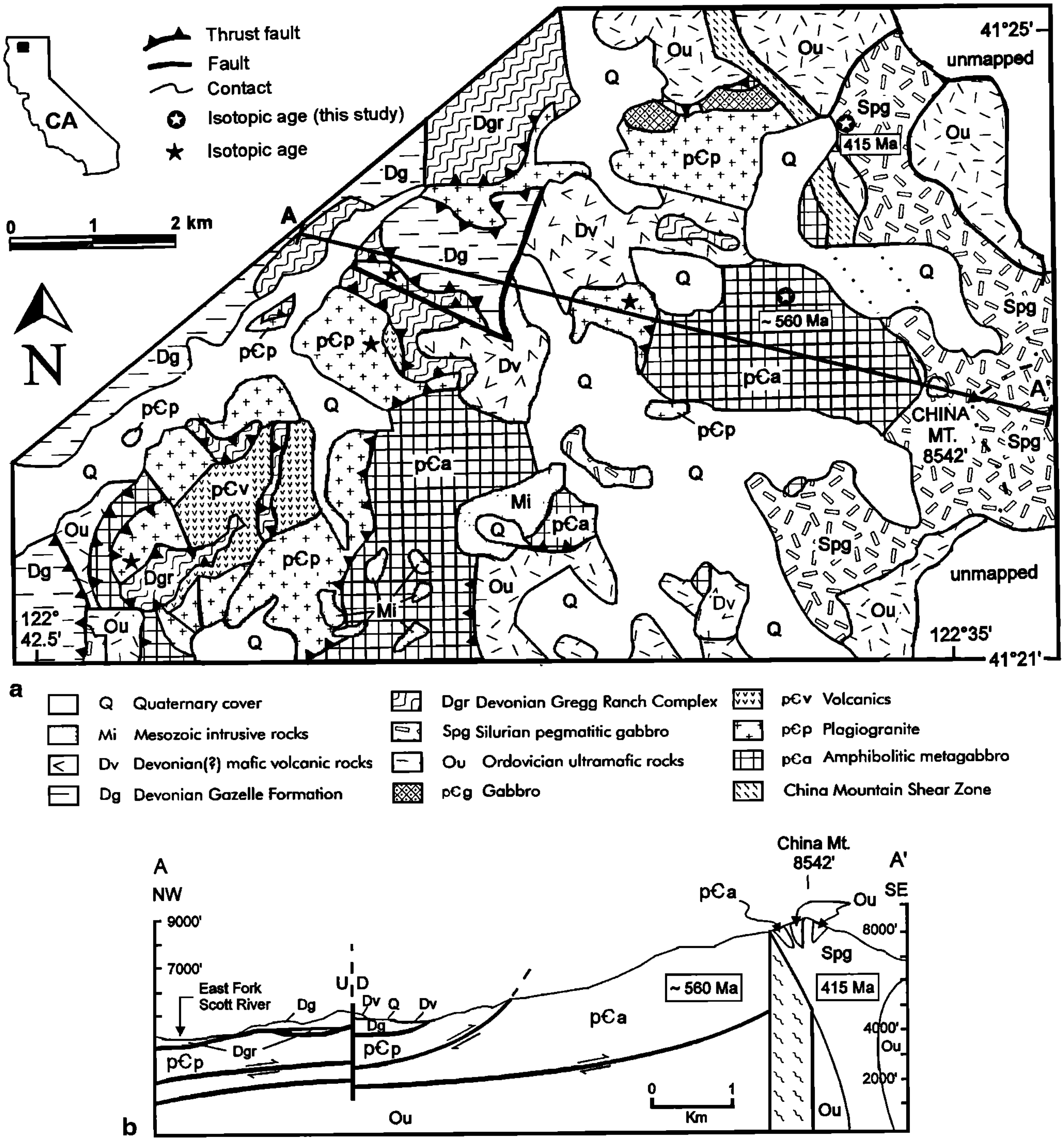

Figure 2. A. Geologic map and cross section of part of the northwestern edge of the Trinity terrane showing locations of dated samples, the Neoproterozoic assemblage, and the pre-Late Silurian suture between Neoproterozoic and Ordovician(?) rocks. B. Cross section shows Neoproterozoic rocks emplaced over Ordovician(?) ultramafic rocks by thrusting. Alternatively, if the vertical ductile shear zone near China Mountain represents a transcurrent fault, then ultramafic rocks west of the shear zone may be Neoproterozoic (i.e., Neoproterozoic rocks west of shear zone were emplaced in a "thick-skinned" deformation).

The crosscutting relationships and isotopic ages presented above document an early Paleozoic deformation in the metagabbro. The timing of deformation of the metagabbro itself is constrained to be post-Neoproterozoic and pre-Late Silurian. This deformation may have occurred prior to or during juxtaposition of the Neoproterozoic rocks and the rest of the Trinity terrane. A minimum age for the amalgamation of Neoproterozoic metagabbro and Ordovician(?) harzburgite is provided by the

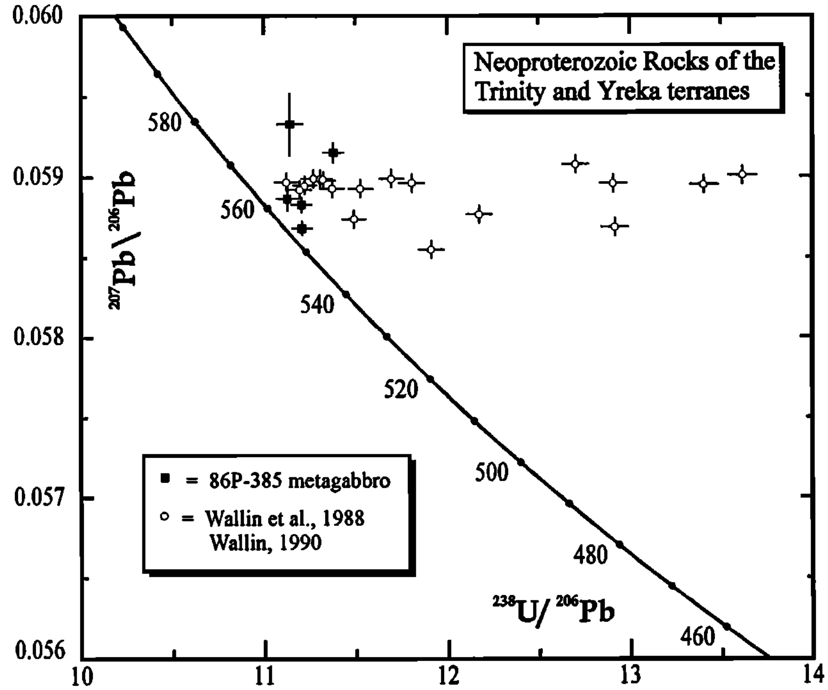

Figure 3. *Tera and Wasserburg* [1972] diagram for zircon from amphibolitic metagabbro of the Neoproterozoic assemblage. Scatter in fractions of sample 86P-385 may be due to minor inherited zircon or to minor perturbation of the isotopic systematics during amphibolite facies metamorphism. Open circles are selected previously published data for a number of tonalites along the northwestern margin of the Trinity terrane and in melange of the Yreka terrane (i.e., not including those fractions containing inherited zircon). Error bars indicate 2σ uncertainties.

Late Silurian isotopic age of the China Mountain pluton. The harzburgite has not been dated directly, but we consider it to be Ordovician in age on the basis of available isotopic data for ultramafic rocks of the Trinity terrane [Jacobsen et al., 1984]. This assumption does not affect the significance of our data because if the harzburgite is not Ordovician, then an even larger portion of the Trinity terrane is not Ordovician, which would underscore the principal tenet of this paper.

Structure and Paleotectonic Setting

Neoproterozoic. Little is known about the petrogenesis of Neoproterozoic rocks in the Trinity terrane, but sparse geochemical data are suggestive of an island-arc origin [Potter and Grunder, 1989]. Furthermore, the relationship between the Neoproterozoic rocks and other components of the Trinity terrane remains enigmatic. Specifically, it remains uncertain whether the Neoproterozoic suite along the northwestern margin of the Trinity terrane is a coherent crustal fragment or simply large tectonic blocks in an accretionary complex [Wallin, 1990]. In either case, the shear zone appears to represent a major early Paleozoic structure that is now nearly vertical where we have mapped it northwest of China Mountain; its original orientation and sense of displacement are unknown (Figure 2).

The apparently linear trace of this steeply dipping structure raises the intriguing possibility that it represents a fossil transform fault. If true, then ultramafic rocks west of this shear zone may be Neoproterozoic as well (Figure 2). Interpretation of the steep dip as primary is consistent with the lack of evidence in both the Yreka and Trinity terranes for tectonic steepening of contacts such as that observed in the northern Sierra terrane (Schweickert et al., 1984; Girty and Schweickert, 1984]. Alternatively, geophysical data indicate that ultramafic rocks underlie strata of the Yreka terrane [LaFehr, 1966; Fuis et al., 1987]. These ultramafic rocks are generally interpreted to be a westward extension of the Trinity terrane, but they are undated. If these ultramafic rocks are Ordovician, then surface exposures of ultramafic rocks at topographically low levels west of the shear zone suggest the Neoproterozoic suite was emplaced in a thin-skinned fashion (Figure 2).

Silurian. The new data reported here indicate that the Late Silurian magmatism in the Trinity terrane recognized by Wallin et al. [1988] was probably widespread and voluminous. The distribution of mafic intrusive complexes of probable Silurian age (Figure 1) is based on Wagner and Saucedo [1987] and our reconnaissance field work. These map units delineate all major occurrences of rocks similar in texture to the China Mountain pluton including pegmatitic gabbro, pegmatitic pyroxenite, hornblende gabbro, diorite, pegmatitic hornblende diorite, and aplite. Previously, all of these rocks were considered provisionally to be Ordovician in age [Wagner and Saucedo, 1987]. We believe, however, that all or many of the undeformed, pre-Mesozoic intrusive rocks of the Trinity terrane may be products of Silurian magmatism because their distinctive lithologies, tex-

Table 1. U-Pb Zircon Isotopic Data and Apparent Ages

Fraction*	Sample Weight, mg	Concentrations†		Measured‡	Radiogenic Isotopic Ratios§				Ages,‖ Ma		
		^{238}U, ppm	^{206}Pb, ppm	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
					Metagabbro						
86P385 nm(0)	1.179	197 8	15 02	2,473	0.05915(10)	0 21593	0.08791(44)	0.7170(37)	543	549	573 ±3
86P385 nm(0)#2	0.678	189.6	14.87	672	0.05933(19)	0 20152	0 08976(48)	0.7342(48)	554	559	579 ±7
86P385 m(0)	0.824	209.0	16.26	917	0.05887(10)	0.21482	0.08986(46)	0.7294(39)	555	556	562 ±3
86P385 m(1)	1 058	217.2	16.72	2,841	0.05869(08)	0.22355	0 08924(45)	0.7222(37)	551	552	556 ±2
86P385 m(2)	0.772	233.5	17.99	1,946	0.05881(08)	0.23191	0.08926(46)	0.7238(38)	551	553	560 ±2
					China Mountain Pluton						
86P389 nm(1)¶	2.381	43.13	2 407	3,571	0.05507(08)	0.12874	0.06449(134)	0.4896(101)	403	405	415 ±2
86P389 m(1)¶	3.546	47.97	2.732	3,508	0.05506(08)	0.12919	0.06580(136)	0.4995(103)	411	412	415 ±2

Isotopic ratios were measured by static multicollection on a VG Sector mass spectrometer at the University of Kansas. Mass fractionation corrections of 0.1% bias per mass unit were applied to Pb data, analytical blanks ranged between 50 and 320 pg total Pb

* Here nm is nonmagnetic; m is magnetic; numbers in parentheses indicate side tilt used on Franz separator at 1.4 amps.

† U corrected for analytical blank; Pb corrected for blank and nonradiogenic Pb.

‡ Uncorrected for blank.

§ Pb corrected for blank and nonradiogenic Pb; U corrected for blank; two sigma uncertainties in last two digits given in parentheses. Uncertainties are based on precision of measured ratios, uncertainty in mass fractionation correction, uncertainties in concentration and isotopic composition of spikes, and uncertainty in isotopic composition of nonradiogenic Pb. The isotopic composition of nonradiogenic Pb used to calculate radiogenic ^{207}Pb and ^{206}Pb was estimated using *Stacey and Kramers* [1975] Pb evolution model. Initial Pb values used to correct measured ratios were 17.8 ±1:15.58 ±.1:37.58 ±1 for metagabbro and 18.06 ±1:15.59 ±.1:37.87 ±1 for pegmatitic gabbro of China Mountain pluton. Blank Pb values used were 18.67 ±1:15.66 ± 1:38.39 ±1.

‖ U decay constants are from *Steiger and Jäger* [1977]. Two sigma uncertainties are calculated using *Ludwig* [1988].

¶ Fractions are spiked with a mixed $^{205}Pb/^{235}U$ tracer; other fractions are spiked with a mixed $^{208}Pb/^{235}U$ tracer

tures, and structure are similar to those of the Upper Silurian China Mountain pluton.

Our interpretation of the Trinity terrane contrasts markedly with that of Boudier et al. [1989], who interpreted these rocks as a stratified Ordovician ophiolite formed at a spreading center. The new Nd data, coupled with those of Jacobsen et al. [1984], further substantiate the polygenetic nature of the Trinity terrane, and they preclude the interpretation that the Trinity terrane is "unreworked" oceanic lithosphere generated at a spreading center [Boudier et al., 1989]. The Nd isotopic composition of the China Mountain pluton (+7.3) and related dikes (+6.6 to +7.3) does not overlap with that of exposed plagioclase lherzolite of the Trinity terrane (+10.4), demonstrating that the more evolved rocks were not derived through simple partial melting of the ultramafic rocks but must have been either derived from melting of a distinct mantle source or contaminated by Sm-depleted crust. In either case, the interpretation that all rocks of the Trinity terrane are a single cogenetic slab of oceanic lithosphere [Boudier et al., 1989] must be discarded. We reiterate the point made by Jacobsen et al. [1984, p. 373], who stated "some ophiolitic bodies represent many distinct stages of evolution of the depleted mantle covering substantial segments of geologic time. In general, it appears that we may not assume both a con-

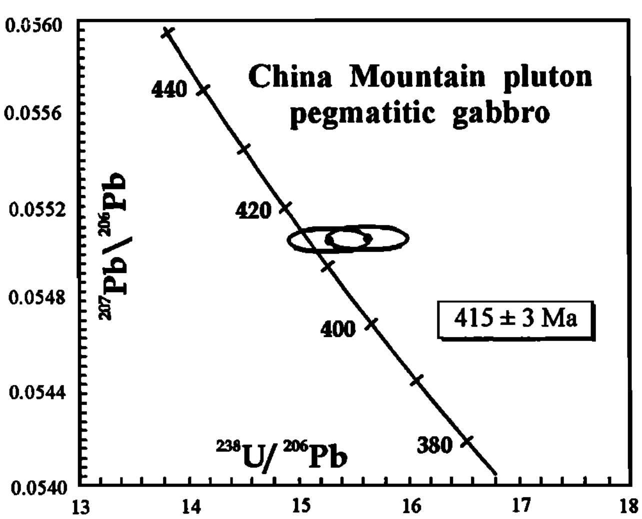

Figure 4. *Tera and Wasserburg* [1972] diagram for zircon from undeformed pegmatitic gabbro of the China Mountain pluton. Ellipses indicate 2σ uncertainties.

Table 2. Sm-Nd Isotopic Data for Sample 89P-389

Parameter	Value
Sm, ppm	0.22
Nd, ppm	0.40
$^{143}Nd/^{144}Nd$	0.513378
Error, 2σ	± 0.000032
$^{147}Sm/^{144}Nd$	0.3314
$\varepsilon_{Nd(0)}$	14.43
$\varepsilon_{Nd(415\ Ma)}$	7.30
T_{DM}	414 Ma
$\varepsilon_{Nd(DM)}$	7.30

Sample was spiked with mixed $^{150}Nd/^{149}Sm$ and dissolved in a mixture of HF and HNO_3 in a sealed Teflon bomb at 220°C for 5 days. After conversion to chlorides, separation of Sm and Nd was accomplished using standard cation exchange techniques and HDEHP on Teflon columns [*White and Patchett*, 1984]. Nd was loaded on triple-Re filaments with H_3PO_4. All analyses were performed on the VG Sector 54 mass spectrometer housed at the Massachusetts Institute of Technology. Nd was analyzed in dynamic multicollector mode with ^{144}Nd = 1.5V, and Sm was analyzed in static multicollector mode with ^{152}Sm = 500mV. Nd data are normalized to $^{146}Nd/^{144}Nd$ = 0.7219. Replicate analyses of La Jolla Nd standard give $^{143}Nd/^{144}Nd$ = 0.511848 ± 0.000010 (2σ; n = 50). Error in the measured $^{147}Sm/^{144}Nd$ ratio is 0.35% (2σ). Epsilon $_{Nd}$ and T_{DM} are calculated using $^{143}Nd/^{144}Nd_{CHUR}$ = 0.512638, $^{147}Sm/^{144}Nd_{CHUR}$ = 0.1967, and $\lambda^{147}Sm = 6.54 \times 10^{-12}\ yr^{-1}$ and the depleted mantle model of DePaolo [1981].

temporaneous and cogenetic origin for the depleted and enriched parts of oceanic crust that are juxtaposed in a single geologic section."

The mafic intrusive complexes of probable Silurian age are broadly distributed throughout the Trinity terrane and their emplacement does not appear to have been controlled by preexisting structures (Figure 1). Thus they do not appear to have intruded along leaky transform or transcurrent faults. We suggest that these mafic complexes represent the roots of a previously unrecognized Silurian magmatic arc developed on the Trinity terrane. The China Mountain pluton (415 Ma) is 15 m.y. older than intrusive rock associated with the Devonian volcanic arc exposed in the nearby Eastern Klamath terrane (Mule Mountain stock (400 Ma) [Albers et al., 1981]). An unresolved question is whether the Silurian magmatism records a discrete magmatic event related to complex tectonic circumstances or whether it simply records the inception of arc magmatism represented by the immature Devonian volcanic arc. The latter interpretation is supported by a recent geochemical study which suggests an island-arc petrogenesis for one of the mafic complexes [Peterson et al., 1991].

Regional Correlation

The recognition of both Neoproterozoic and Late Silurian plutonism in the Trinity terrane strengthens tectonostratigraphic correlations that have been proposed between the eastern Klamath Mountains and the northern Sierra terrane [Speed, 1979; Schweickert and Snyder, 1981; Wallin et al., 1988]. Igneous rocks of both Neoproterozoic and Silurian age have been identified in the Shoo Fly Complex of the northern Sierra terrane as well [Saleeby et al., 1987; Saleeby, 1990].

Conclusions

1. The China Mountain pluton in the Trinity terrane crystallized at 415 ±3 Ma. Most, if not all, of the lithologically similar plutons in the Trinity terrane are probably Silurian as well.
2. Silurian intrusive rocks of the Trinity terrane represent the roots of a Silurian intraoceanic volcanic island-arc rather than Ordovician late-stage ophiolitic magmas as has been proposed previously.
3. The Late Silurian China Mountain pluton stitches a ductile shear zone that juxtaposes a Neoproterozoic crustal fragment and Ordovician mantle tectonites.

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