Reports

Mantle-Derived Peridotites in Southwestern Oregon: Relation to Plate Tectonics

Abstract. *A group of peridotites in southwestern Oregon contains high-pressure mineral assemblages reflecting recrystallization at high temperatures (1100° to 1200°C) over a range of pressure decreasing from 19 to 5 kilobars. It is proposed that the peridotites represent upper-mantle material brought from depth along the ancestral Gorda–Juan de Fuca ridge system, transported eastward by the spreading Gorda lithosphere plate, and then emplaced by thrust-faulting in the western margin of the Cordillera during late Mesozoic time.*

The origin of ultramafic rocks in orogenic belts has long been a subject of debate (*1, 2*). Despite careful field and petrologic studies of these enigmatic rocks in recent years, a unifying theme has failed to emerge, and instead, several different modes of origin now seem plausible (*2*). According to models of plate tectonics, ultramafic rocks of the alpine type may represent fragments of the oceanic crust and upper mantle transported by spreading lithosphere plates and then tectonically emplaced in orogenic belts (*3*). In the course of a comparative study of selected ultramafic rocks in northwestern California and southwestern Oregon, we discovered that a group of peridotites located in coastal southwestern Oregon contains high-pressure mineral assemblages, and the petrologic data are consistent with the idea that these assemblages are derived from the upper mantle.

Southwestern Oregon is situated on the western margin of the Cordilleran mobile belt, in proximity to the seismically active Gorda–Juan de Fuca ridge system and its associated transform faults (*4, 5*) (Fig. 1). Late Cenozoic underthrusting of the American lithosphere plate by the Gorda plate in this region is indicated by the presence of magnetic anomaly number 3 (5 million years old) beneath the continental slope and by deformation of late Cenozoic, possible trench sediments at the base of the continental slope (*6*). The late Cenozoic Cascade volcanoes appear to represent a volcanic arc complementary to the inferred trench, although an active Benioff zone defined by deep-focus earthquakes is not known at the present time (*4, 5*).

As in California (*7*), Mesozoic underthrusting in Oregon and Washington is inferred from mélange terranes associated with volcanic rocks and serpentinite sheets. During the culmination of late Mesozoic mountain-building, sedimentary and volcanic rocks were deformed and extensively thrust-faulted, metamorphosed, and intruded by igneous plutons (*8–10*). The entire Mesozoic complex, including the thrust plates, was overlapped by Eocene strata. Then all these rocks and thrust plates were cut by late Cenozoic vertical faults trending north-northwest, presumed to be related to the San Andreas system (*9, 11*) (Fig. 1).

That the region offshore from northwestern California and southwestern Oregon is unusual in showing structural patterns related to spreading and underthrusting as well as faulting of the San Andreas type was suggested by Tobin and Sykes (*5*) and confirmed by Silver (*6*). Spreading ceased south of the Mendocino fracture zone after the East Pacific Rise was destroyed there by collision with the American lithosphere plate (*4, 5*), but it has continued farther north. As the rise disappeared farther south, the San Andreas transform system became fully developed and similar faults were propagated northward along the western edge of the American plate into Oregon, as evidenced by onshore geology (*9*) and earthquake first motions (*12*). An unusually complex pattern of contemporaneous strike-slip faulting and underthrusting has resulted at the edge of the continental (American) plate.

Peridotite masses, serpentinized to varying degrees, characterize southwestern Oregon. The four of interest (Fig. 1) are in fault contact with surrounding rocks, and metasomatic reaction zones (rodingites) commonly are present along contacts, an indication of the relatively low temperatures of final emplacement (*13*). The Vondergreen Hill and Carpenterville peridotites, located near the coast (Fig. 1, Nos. ① and ②), have been intensely sheared. The Carpenterville mass consists of large, randomly oriented blocks of peridotite, pyroxenite, serpentinite, gabbro, and Jurassic sedimentary and volcanic rocks, all intimately sheared together in a matrix of crushed material, whereas the Vondergreen Hill mass consists solely of peridotite blocks in a sheared serpentinite matrix. Farther inland, the

Table 1. Chemical analyses of peridotites, recalculated to 100 percent (by weight) on a water-free basis (total Fe as FeO). Sample 1, average value for six peridotites (range of values is given in parentheses) from southwestern Oregon: four from Vondergreen Hill and one each from Carpenterville and Signal Butte; sample 2, lherzolite, Central Indian Ridge, Indian Ocean (*16*); sample 3, St. Paul's Rocks (WD 55), Atlantic Ocean (*18*); sample 4, Lizard, England, average (*19*); sample 5, pyrolite (*20*).

Oxide	Sample				
	1	2	3	4	5
SiO_2	44.1 (43.4–44.7)	43.69	44.63	44.77	45.18
Al_2O_3	4.0 (3.6–4.2)	3.13	4.10	4.16	3.54
Cr_2O_3	0.4 (0.4–0.5)	0.55	0.46	0.40	0.43
FeO	9.1 (8.7–9.8)	7.34	7.91	8.21	8.45
MgO	40.0 (38.7–41.2)	40.30	39.12	39.22	37.50
CaO	2.4 (1.9–2.7)	4.28	2.87	2.42	3.08
Na_2O		0.23	0.32	0.22	0.57
K_2O		.02	.07	.05	.13
TiO_2		.01	.12	.19	.71
MnO		.07	.13	.11	.14
P_2O_5			.02	.01	.06
NiO		0.38	.25	.24	.20
CoO					.01
Total	100.00	100.00	100.00	100.00	100.00

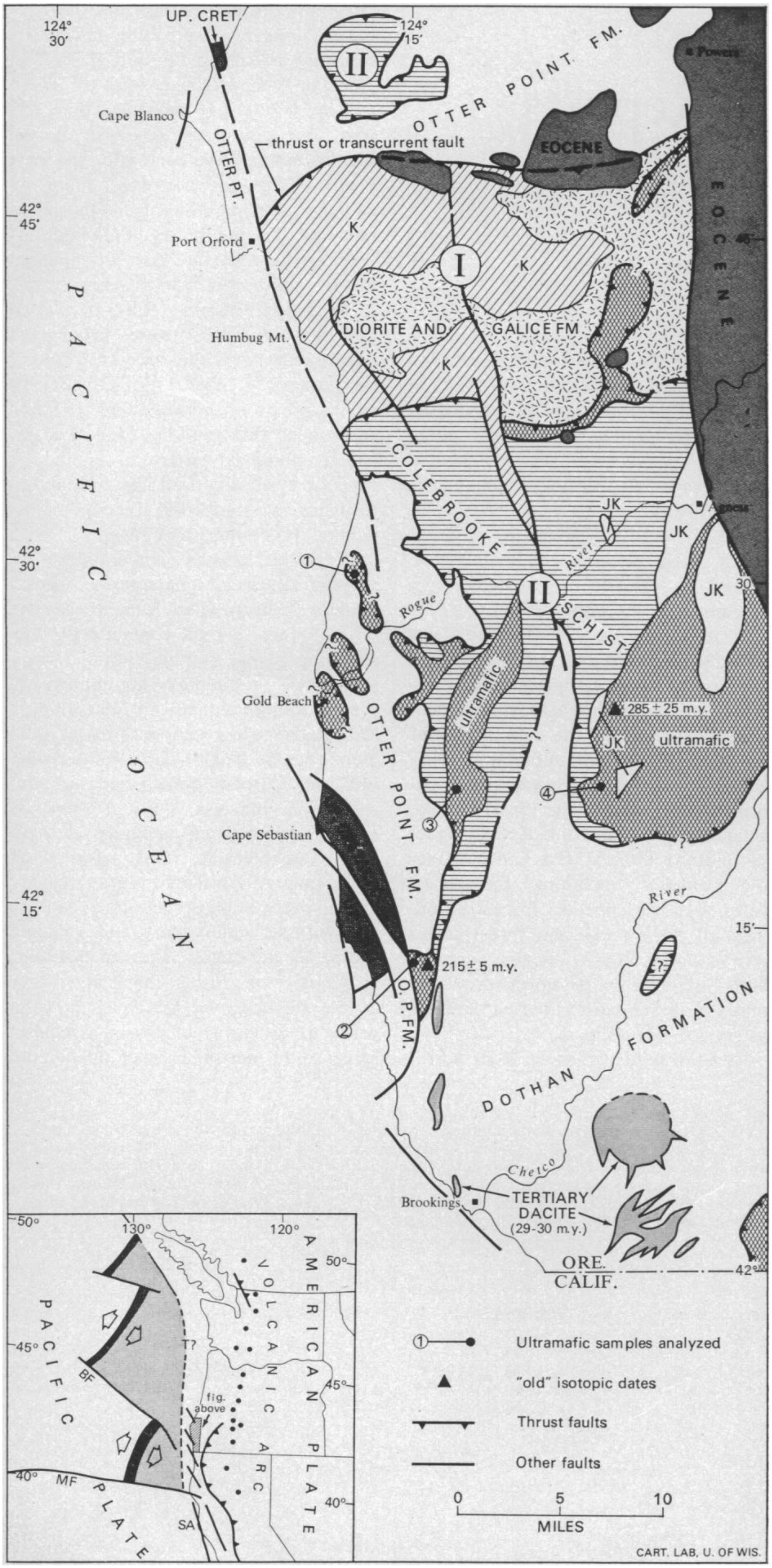

Fig. 1. Generalized geologic map of the coastal region of southwestern Oregon showing four ultramafic rock localities and two isotopic date localities discussed in text [adapted from (*8–10, 14*); see (*25*)]. Inset map shows location of region studied with respect to Gorda–Juan de Fuca ridge system and associated transform faults, the Cascade volcanic arc, and San Andreas fault system; *T?* designates site of inferred filled trench along margin between American and Gorda (shaded) lithosphere plates. Sawtooth symbol denotes major late Mesozoic thrust-fault boundary between Coast Range geologic province and the Cordilleran orogen [adapted from (*4*)].

Signal Butte and Snow Camp peridotites are much larger and less sheared, exhibiting semiconcordant contacts with surrounding strata and extending north-south for many miles (Fig. 1, Nos. 3 and 4). Both bodies are comprised of massive peridotite with minor serpentinite, cut by small gabbroic dikes. Dioritic stocks also occur within the Snow Camp peridotite. In the past, all four bodies were interpreted as narrow, steeply dipping intrusive rocks sheared and serpentinized during post-intrusive faulting (*9, 14*). Recently, however, Coleman (*10*) has proposed the plausible hypothesis that most of the ultramafic bodies are associated wih low-dipping late Mesozoic thrust sheets modified along late Cenozoic vertical fault zones (Fig. 1). At least one, and possibly two, major sheets are indicated, and Coleman believes (*10*) that associated peridotites and schists (block II of Fig. 1) may represent a series of several additional thrust sheets. Where serpentinization was thorough, the ultramafic masses appear to have risen as diapirs or tectonic intrusions through more dense surrounding rocks to further complicate the region.

We have analyzed six samples of peridotite, four from Vondergreen Hill and one each from Carpenterville and Signal Butte, for Si, Fe, Mg, Ca, Cr, and Al by electron probe techniques (*15*). Except for a slight enrichment in total Fe, the peridotites closely resemble in chemistry peridotites from mid-ocean ridges (*16–18*), high-temperature peridotites (*19*), and the hypothetical mantle material, pyrolite (*20*) (Table 1).

Mineralogically, specimens from all four peridotites are the same, since each contains forsterite, enstatite, diopside, and accessory spinel. Although serpentinization is appreciable in many

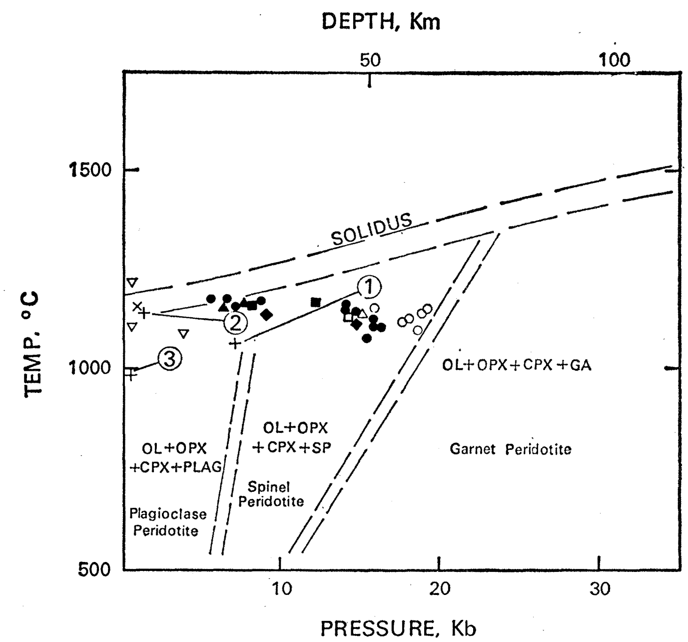

Fig. 2. Conditions of recrystallization for peridotites of southwestern Oregon, based on O'Hara's pyroxene grid for natural aluminous four-phase peridotites (*22*). ○, ●, Vondergreen Hill; □, ■, Carpenterville; △, ▲, Signal Butte (open symbols, augen or coarse-grained pyroxene; solid symbols, matrix pyroxene); ♦, Snow Camp; ①, Lizard, England (primary mineral assemblage); ②, Horoman, Japan (primary); ③, Miyamori, Japan (primary); +, recrystallized assemblages for ①, ②, and ③; ▽, New Zealand peridotites; X, Bushveld peridotite.

samples, producing mesh and bastite textures, sufficient amounts of anhydrous silicates are preserved from which to deciper the original textures. The Vondergreen Hill peridotite is texturally distinct from the other three, in that it contains strained augen ($\leqq 10$ mm) of ensatite, diopside, and forsterite in a fine-grained matrix of forsterite, enstatite, diopside, and spinel. The other peridotites have inequigranular textures, in which large, anhedral pyroxenes ($\leqq 6$ mm) are set in a medium-grained, allotriomorphic granular matrix of forsterite, two pyroxenes, and spinel. Nonuniform extinction and straining are evident in silicates from all four localities, but these features are most conspicuous in the Vondergreen Hill peridotite. Exsolution lamellae of diopside are prominent in coarse-grained enstatite, but lamellae are absent or only poorly developed in coarse-grained diopside, and absent in matrix pyroxenes. Spinel is anhedral, pale brownish-yellow to brown, rimmed by magnetite, and interstitial to matrix silicates in all specimens.

Microprobe analyses (*21*) indicate that the silicates are relatively uniform with respect to the chemistry of the major elements. Values (in mole percent) are: Forsterite: forsterite, 90 to 91; enstatite: wollastonite, 1 to 3; enstatite, 88 to 90; ferrosilite, 9 to 10; diopside: wollastonite, 47 to 49; enstatite, 48 to 49; ferrosilite, 4 to 5. The Al_2O_3 contents of the pyroxenes are exceptionally high (up to 5.60 percent for enstatite, 6.88 percent for diopside), but variable within a given specimen, ranging, for example, from 3.36 to 5.15 percent for enstatite and from 4.97 to 6.43 percent for diopside in a sample of Vondergreen Hill peridotite. Invariably, the coarse-grained pyroxenes contain more Al_2O_3 than associated matrix pyroxenes do. Spinels in the Vondergreen Hill, Carpenterville, and Signal Butte peridotites are unusually rich in $MgAl_2O_4$ [$Mg/(Mg + Fe^{2+}) = 0.74$ to 0.81; $Cr/(Cr + Al) = 0.12$ to 0.21], whereas spinel in the Snow Camp mass contains slightly more iron and chromium [$Mg/(Mg + Fe^{2+}) = 0.69$ to 0.75; $Cr/(Cr + Al) = 0.30$ to 0.34].

Conditions of recrystallization for the peridotites of southwestern Oregon have been estimated by means of O'Hara's pyroxene grid (*22*), based on the composition of clinopyroxene in a four-phase assemblage consisting of clinopyroxene (CPX), orthopyroxene (OPX), olivine (OL), and an aluminous phase, either plagioclase, spinel, or garnet (Fig. 2). As the plots for coarse-grained and matrix clinopyroxenes in Fig. 2 indicate, the peridotites were derived from depths of 50 to 60 km, and recrystallization took place at high and perhaps slightly increasing temperatures on the order of 1100° to 1200°C as the peridotites were brought to shallower depths. The prevalence of disequilibrium assemblages is demonstrated by different Al_2O_3 and Cr_2O_3 contents, and thus different inferred temperatures and pressures of recrystallization, for individual clinopyroxene grains in a given peridotite specimen. Despite this, however, partitioning of Mg and Fe^{2+} among forsterite, enstatite, diopside, and spinel indicates uniformly high temperatures of recrystallization (*23*). The apparent equilibrium distribution of Mg and Fe^{2+} in these disequilibrium assemblages is due to recrystallization within a restricted temperature interval but over a wide range of pressure, combined with the relative insensitivity of Mg-Fe^{2+} partitioning to changes in pressure. If recrystallization of the anhydrous phases were related to tectonic emplacement of the peridotites in the continental crust, one would expect much lower temperatures of recrystallization, particularly because blueschist and greenschist facies metamorphic rocks (Colebrooke Schist) are widely developed in this region, and rodingites occur at peridotite contracts. Clearly, the episode of high-temperature recrystallization recorded in these peridotites is earlier than, and unrelated to, their ultimate emplacement in the continental crust.

We propose that this group of peridotites represents fragments of the upper mantle originally brought from depth beneath the ancestral Gorda–Juan de Fuca ridge system. During this initial stage of development, high-temperature recrystallization occurred, which resulted in the breakdown of alumina-rich pyroxenes with the concomitant formation of spinel and less-aluminous matrix pyroxenes. Partial melting and generation of gabbros or basalts may have taken place at depths of 20 to 25 km, as suggested by the occurrence of gabbroic dikes in the peridotites and by the approach of the recrystallization trend toward the solidus in Fig. 2. The peridotites and associated rocks were then carried eastward by the spreading Gorda plate, eventually to be emplaced by thrust-faulting in the western margin of the Cordillera. Low-temperature serpentinization and formation of rodingites probably first occurred at shallow depths beneath the ridge, continued during eastward transport, culminated during tectonic emplacement, and persisted through Cenozoic time; perhaps these processes are continuing today (*24*).

The sequence of tectonic events summarized above provides an explanation for what were previously thought to be anomalous isotopic dates. Many K-Ar dates indicate that the late Mesozoic regional metamorphism and dioritic plutonism in southwestern Oregon and northwestern California occurred chiefly between 130 and 145 million years ago (*8, 9*), but dioritic and gabbroic masses within the Carpenterville and Snow Camp peridotites yielded K-Ar dates on amphiboles of 215 ± 5 and 285 ± 25 million years, respectively (*9*). The mineralogic evidence from the peridotites is consistent with the previously suggested hypothesis that several large blocks of old diorite and gabbro have been carried up within the mantle peridotite masses, either with their isotopic clocks left intact, or with excess argon having been incorporated into their minerals in a high-pressure environment.

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21. Polished thin sections were prepared for five peridotite specimens from Vondergreen Hill, two each from Carpenterville and Signal Butte, and one from Snow Camp. In the mineral analysis we used an electron probe (Applied Research Labs) and followed the procedures recommended by A. E. Bence and A. L. Albee [*J. Geol.* **76**, 382 (1968)]. Reduction of probe data was performed on a computer (Univac 1108), with the aid of a program written by D. Gast.
22. M. J. O'Hara has established a provisional petrogenetic grid for the system, CaO, (Mg, Fe^{2+})O, $(Al,Cr,Fe^{3+})_2O_3$, SiO_2, on the basis of experimental studies. Two sets of intersecting curves, related to the CaO and R_2O_3 (where R is a trivalent metal) contents of clinopyroxene, permit the determination of temperature and pressure conditions from the chemical composition of clinopyroxene in a four-phase assemblage [M. J. O'Hara, in *Ultramafic and Related Rocks*, P. J. Wyllie, Ed. (Wiley, New York, 1968), p. 383].
23. L. G. Medaris, in preparation; E. D. Jackson, in *Magmatic Ore Deposits*, H. D. B. Wilson, Ed. [*Econ. Geol. Monogr. 4* (1969), p. 41]; R. Kretz, *J. Geol.* **71**, 773 (1963).
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25. Mesozoic ocean floor underthrusting apparently culminated in late Cretaceous time with thrusting of at least one and probably more large plates (for example, Fig. 1, block II) over late Jurassic Otter Point and Dothan formations, which are similar to the Franciscan complex of California. Eocene (and possibly latest Cretaceous) strata then were deposited. Finally, vertical faults trending northwest and dacite intrusions formed in post-Eocene time. Block I contains Jurassic greenschist and diorite basement unconformably overlain by Lower Cretaceous strata (Fig. 1, *K*), all of which represent Klamath Province rocks apparently transported relatively at least 25 miles (40 km) from the east either by thrusting or by transcurrent faulting. Block II (Fig. 1) contains schists transitional between blueschist and greenschist facies, ultramafic masses, and unmetamorphosed uppermost Jurassic(?) and Lower Cretaceous strata (*JK*), all of unknown location prior to thrusting. The ultramafic masses are inferred to have been transported eastward from the Gorda ridge and structurally injected into the Colebrooke Schist by underthrusting. Subsequently the entire complex was emplaced in its present position during culmination of the Mesozoic episode of spreading.
26. Supported by grants from the Wisconsin Alumni Research Foundation. We are indebted to R. G. Coleman for permission to include his thrust interpretations in Fig. 1 and for his constructive criticism during the evolution of this paper. We thank C. Craddock and C. V. Guidotti for reading the manuscript, and E. D. Glover for providing invaluable assistance in the operation of the electron probe.

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A Radar Snapshot of Venus

Abstract. *A radar brightness map of Venus has been obtained. It reveals interesting surface features and much structure over a large area.*

We have taken advantage of the recently increased capability of the Jet Propulsion Laboratory's Goldstone Tracking Station to obtain a radar "snapshot" of the planet Venus. A fairly extensive equatorial region (13,500 by 7,500 km) has been mapped. The resultant resolution of 80 km is the best yet achieved from Venus. The bright feature Alpha shows up very clearly, and much of its detail is revealed. There is also a host of interesting radar-bright and radar-dark objects. Flaws in the radar map can be traced to instrumental effects.

Venus never subtends an angle greater than 0.018° from Earth. Since the narrowest radar antenna beam available is much larger (0.14°), adequate resolution for mapping must come from another source. We have used time delay (or range gates) and frequency shift to obtain the needed resolution.

Range-gating has the effect of dividing the planet into circles concentric with the sub-Earth point. It is accomplished by modulating the transmitted signals with a fast waveform and by applying the inverse modulation to the received signals. Only signals with the proper time delay can get through the range gate.

Frequency shift is the result of Venus's rotation, acting through the Doppler effect. Regions with different line-of-sight velocities are distinguishable by their differing frequency shifts. Frequency analysis of the range-gated echoes provides the second dimension for radar mapping. The resulting spectrograms also divide the planet into concentric circles but at right angles to the circles produced by range-gating (see Fig. 1).

Note that there is an essential ambiguity in this method. Points symmetrically placed about the Doppler equator have the same time delay and frequency shift. The resolution of this ambiguity is discussed later.

For this experiment we used a 40-km