Subduction-zone magnetic anomalies and implications for hydrated forearc mantle

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ABSTRACT

Continental mantle in subduction zones is hydrated by release of water from the underlying oceanic plate. Magnetite is a significant byproduct of mantle hydration, and forearc mantle, cooled by subduction, should contribute to long-wavelength magnetic anomalies above subduction zones. We test this hypothesis with a quantitative model of the Cascadia convergent margin, based on gravity and aeromagnetic anomalies and constrained by seismic velocities, and find that hydrated mantle explains an important disparity in potential-field anomalies of Cascadia. A comparison with aeromagnetic data, thermal models, and earthquakes of Cascadia, Japan, and southern Alaska suggests that magnetic mantle may be common in forearc settings and thus magnetic anomalies may be useful in mapping hydrated mantle in convergent margins worldwide.

Keywords: Cascadia convergent margin, magnetic anomalies, gravity anomalies, hydrated mantle, serpentinization, earthquakes.

INTRODUCTION

At a depth of ~40–50 km, metabasalt within subducting ocean crust is transformed to eclogite, releasing large amounts of water into overlying lithosphere; the water hydrates upper-mantle peridotite, producing serpentine minerals (Kirby et al., 1996; Peacock et al., 2002). Serpentinization decreases the density of peridotite and produces magnetite. As peridotite is serpentinized from 0% to 95%, magnetic susceptibility increases by several orders of magnitude, and remanent magnetization increases by at least an order of magnitude (Saad, 1969). Density, however, decreases from >3000 kg/m^3 to ~2500 kg/m^3 (Christensen, 1966; Saad, 1969). Thus, serpentinite has the unusual property of being low in density while having very high magnetization.

Thermal models (Oleskevich et al., 1999) indicate that much of the mantle wedge at many subduction zones is cooler than the Curie temperature of magnetite, 580 °C at atmospheric pressure. Moreover, the high pressure and relatively high temperature at mantle depths enhance magnetization in several ways. Rock-magnetic observations show that magnetic susceptibility (Dunlop, 1974) and viscous remanent magnetization (Dunlop, 1983) increase as single-domain magnetite approaches its Curie point, and the Curie point increases with hydrostatic pressure (e.g., Schult, 1979). Thus, as proposed by Hyndman and Peacock (2003), we should expect to see evidence for hydrated mantle in magnetic anomalies along forearcs.

GEOPHYSICAL OBSERVATIONS

A teleseismic transect (Fig. 1A, white dashed line) across the Oregon convergent margin provides convincing evidence for hydration of continental mantle above the subducting Juan de Fuca plate (Bostock et al., 2002). Beneath the arc and backarc, continental Moho is well defined, with low-velocity crust above high-velocity mantle. However, where the descending Juan de Fuca plate intersects the Moho, the expected velocity contrast across the Moho is either missing or inverted, with higher-velocity crust overlying lower-velocity mantle. Bostock et al. (2002) interpreted these seismic results as evidence for hydrated mantle and estimated the mantle wedge to be 50%–60% serpentinized. Although the Cascadia margin is warm relative to other subduction zones, thermal models (Bostock et al., 2002) indicate that most of the hydrated mantle wedge is at depths shallower than the Curie isotherm of magnetite. The Cascadia forearc is thus an excellent place to test the ability of magnetic anomalies to illuminate the hydrated mantle wedge.

Aeromagnetic data from western Oregon and Washington display a distinctive pattern of anomalies (Fig. 1A) reflecting the Tertiary history of the Cascadia forearc. Prominent

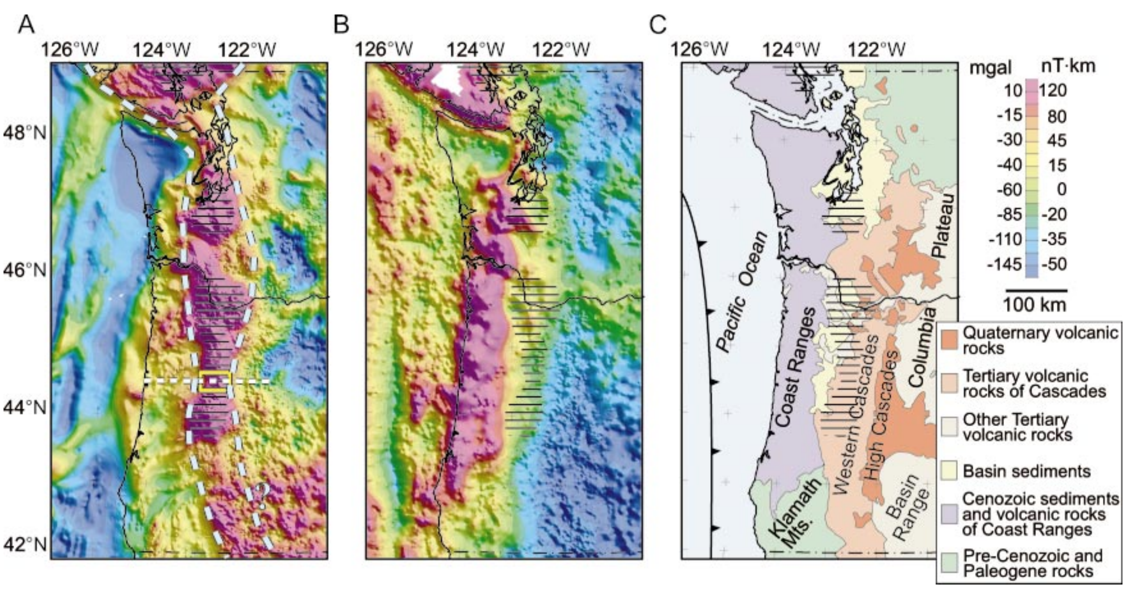


Figure 1. Cascadia potential-field anomalies and geology. A: Aeromagnetic anomalies, transformed to magnetic potential (in nT·km; Blakely, 1995, p. 343–346). B: Bouguer gravity anomalies onshore, free-air anomalies offshore. C: Generalized geology. Blue dashed lines in A bound magnetic anomalies interpreted here as partially caused by hydrated mantle. Black horizontal line pattern shows location of magnetic anomalies of highest amplitude. White dashed line is location of seismic transect (Bostock et al., 2002) showing evidence of serpentinized forearc mantle (in yellow rectangle).

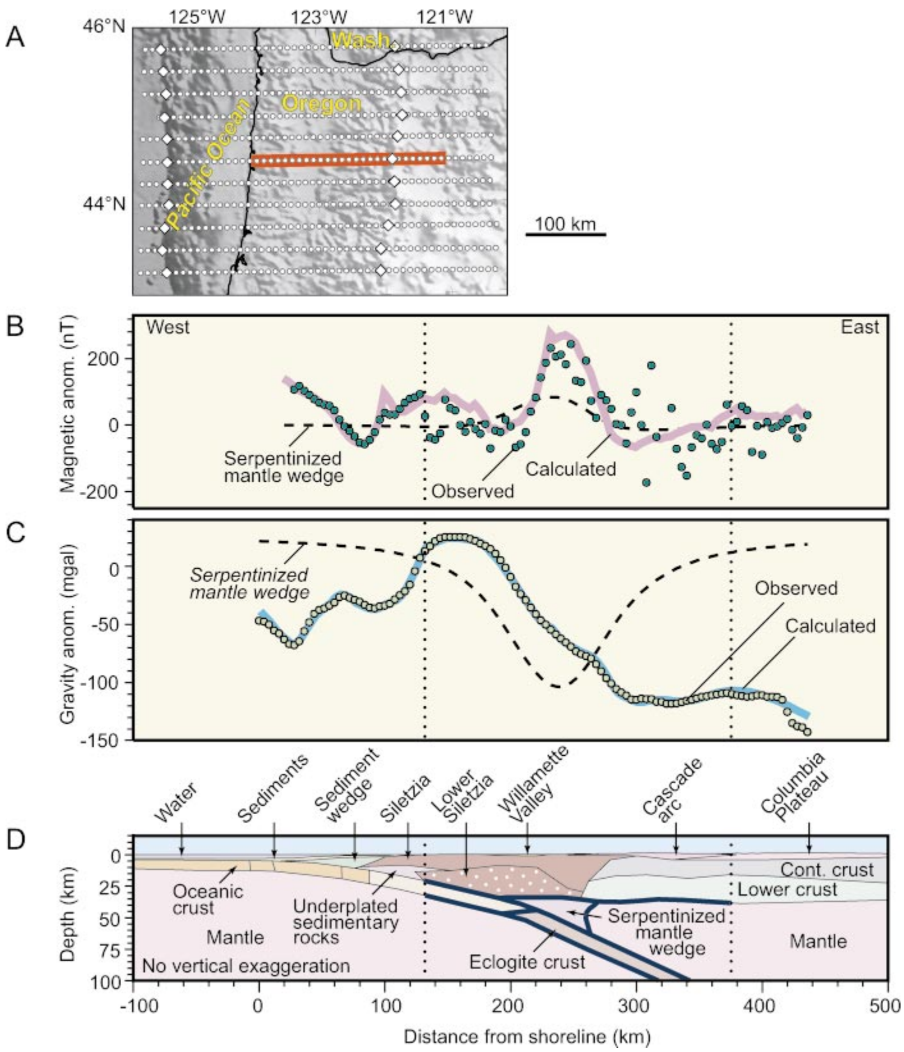


Figure 2. Simultaneous gravity and magnetic model of Oregon forearc. A: Topography and bathymetry of western Oregon and offshore regions. White dotted lines show locations of 11 topographic, magnetic, and gravity profiles used for crust and upper-mantle model. White diamonds are pinpoints along deformation front offshore and Holocene arc onshore. Red line is location of seismic transect (Bostock et al., 2002). B: Stacked magnetic profile, average of 11 profiles shown in A. C: Stacked gravity profile. D: Crust and upper-mantle model. In B and C, dashed lines labeled "serpentinized mantle wedge" refer to gravity and magnetic response of mantle wedge alone. Vertical dotted lines in B, C, and D indicate limits of teleseismic transect, and bold lines in D indicate contacts taken directly from that seismic interpretation (Bostock et al., 2002). See Table 1 for physical properties used in model.

TABLE 1. PHYSICAL PROPERTIES USED IN GRAVITY AND MAGNETIC MODEL (FIG. 2)

Unit	Density (kg/m^3)	Magnetization (A/m)
Willamette Valley	2580	0.00
Cascade arc	2620	0.50
Columbia plateau	2600	0.83
Continental crust	2670	0.50
Lower crust	3090	0.10
Underplated sedimentary rocks	2740	0.00
Ocean crust	2850	0.55, 1.12, −1.23, 1.57, 2.20
Eclogite ocean crust	3330	0.00
Sediment wedge	2740	0.00
Trench sediments	1880	0.00
Mantle wedge	2780	1.38
Siletzia	2920	1.10
Lower Siletzia	3100	0.00
Mantle	3300	0.00
Water	1030	0.00

high-amplitude magnetic anomalies overlying the Western Cascades and Willamette Valley have been interpreted as being caused by Miocene granodiorite intrusions of the Western Cascades (Finn, 1991) or by the eastern edge of Siletzia (e.g., Wells et al., 1998), the accreted basalt basement of the Oregon and Washington forearc. Crustal rocks are fundamental contributors to Cascadia forearc magnetic anomalies, but Figure 1 illustrates an interesting conundrum: although magnetic rocks typically have high densities, the highly magnetic region of the Cascadia forearc (Fig. 1, horizontal line pattern) has no comparable gravity signature and is displaced well east of the high-gravity region. In addition, the high-amplitude magnetic anomaly (Fig. 1) appears to have significant long-wavelength components, indicating that part of this anomaly originates from great depths. Through the use of matched-filter techniques (Phillips et al., 1993), we estimate that the Cascadia magnetic anomaly includes contributions from deeper than 33 km depth.

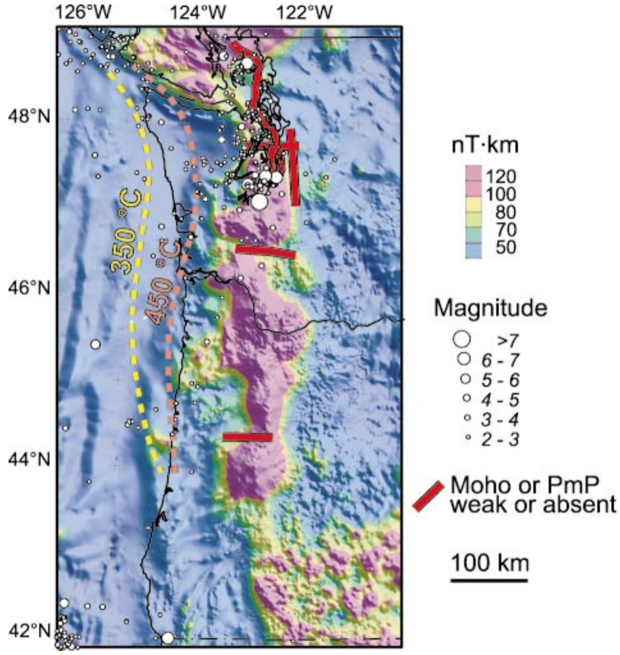
The spatial offset between high-amplitude gravity and magnetic anomalies and their long-wavelength character suggests that shallow crustal rocks cannot fully account for these observations. Thus, we propose that deep-seated, highly magnetic, low-density rocks also contribute to high-amplitude magnetic anomalies in Oregon, precisely the unique properties offered by the serpentinized mantle wedge observed in seismic velocities (Bostock et al., 2002).

GEOPHYSICAL MODEL

Magnetic sources within the continental mantle would produce anomalies at the surface with low amplitudes and long wavelengths. Could magnetic mantle contribute to the dramatic anomalies actually observed? To answer this question, we developed a simultaneous gravity and magnetic forward model of the Oregon forearc consistent with the extensive literature available on the geophysical underpinnings of this region (Bostock et al., 2002; Couch and Riddihough, 1989; Tréhu et al., 1994; Fleming and Tréhu, 1999; Romanyuk et al., 2001). Figure 2 shows representative gravity and magnetic profiles with respect to the teleseismic transect (Bostock et al., 2002). These profiles were constructed in order to emphasize two-dimensional characteristics of the forearc while subduing three-dimensional geologic variations. They were calculated by extracting 11 east-west gravity, magnetic, and topographic-bathymetric profiles from gridded databases (Fig. 2A); linearly interpolating each to an even sample interval, by using as pinpoints the deformation front offshore and the Holocene arc onshore; and averaging them together.

In developing the gravity and magnetic model (Fig. 2D), key aspects of the seismic section from Bostock et al. (2002) were honored: the depth to continental Moho, the depth and thickness of the descending Juan de Fuca plate, and the geometry of the hydrated mantle wedge. The mantle wedge was assigned a density of 2780 kg/m^3 and a magnetization of 1.38 A/m on the basis of rock-magnetic studies of ultramafic rocks (Saad, 1969). Other lithologies were assigned densities and magnetizations (Table 1) compatible with published models (Finn, 1990; Fleming and Tréhu, 1999; Romanyuk et al., 2001). Siletzia is as thick as 34 km in our model, in agreement with results from seismic refraction data (Tréhu et al., 1994). Surprisingly, the data re-

Figure 3. Magnetic anomalies (transformed to magnetic potential in nT·km), intraslab earthquake epicenters (Karen Meagher, 2001, personal commun.), and location of missing Moho in controlled source seismic and tomographic studies (Brocher et al., 2003). Colored dashed lines are slab temperatures (Oleskevich et al., 1999). Earthquakes are mainly those with M > 2 that occurred from 1980 to 1998 but also include earlier events of significant magnitude.



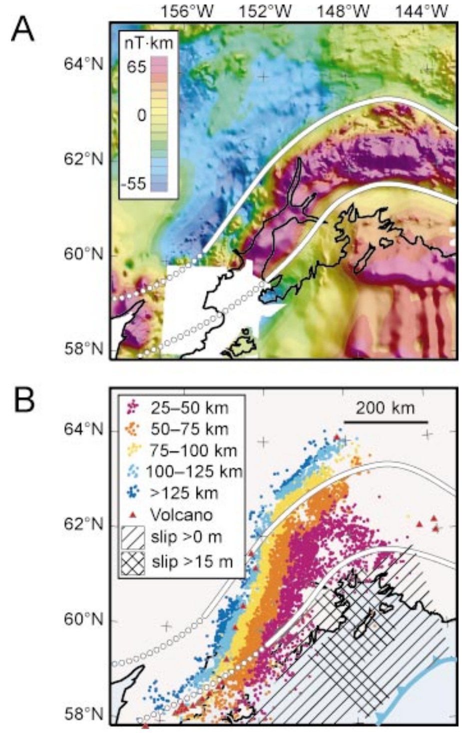


Figure 4. A: Aeromagnetic anomalies of Alaska (Saltus et al., 1999), transformed to magnetic potential (in nT·km). B: Intraslab earthquakes occurring between 1988 and 1998, colored by depth (Ratchkovski and Hansen, 2002). White lines (dotted where less certain) in A and B show extent of southern Alaska deep magnetic high (Saltus et al., 1999). Cross-hachure pattern is region of coseismic slip during 1964 Prince William Sound megathrust earthquake (Johnson et al., 1996).

quire that we model the lower part of Siletzia as relatively nonmagnetic. The depth and temperature of lower Siletzia are favorable for greenschist metamorphism (Peacock et al., 2002), and we suggest that metabasalts in this fluid-rich environment may be relatively poor in magnetite. The fit to observed gravity is excellent, but we did not attempt to fit the details of the composite magnetic profile except to model appropriate wavelengths and amplitudes. We conclude that a low-density, high-magnetization mantle wedge is consistent with accepted geologic models of the Oregon forearc and contributes about one-third of the observed magnetic anomaly amplitude.

DISCUSSION

Figure 3 shows locations where Moho or upper-mantle reflections are weak or absent (Brocher et al., 2003). Taken together, these locations form a narrow swath along the Willamette Valley and Puget Lowland, interpreted as evidence for hydrated mantle along the Cascadia margin (Brocher et al., 2003). Figure 3 shows general agreement between the locations of missing Moho and high-amplitude magnetic anomalies, supporting that earlier interpretation.

Petrologic models (Kirby et al., 1996; Peacock et al., 2002) predict a causal connection between intraslab earthquakes and hydrated forearc mantle. Water released from the descending slab starting at ~40 km depth promotes both brittle failure within the slab and hydration of the overlying mantle. Thus, magnetic anomalies originating from serpentinized mantle should spatially correlate with intraslab earthquakes. Figure 3 shows Cascadia intraslab earthquakes and magnetic anomalies. A spatial correlation appears to exist in Washington, but intraslab earthquakes are rare in Oregon, where magnetic anomalies are well developed (Fig. 3). Eclogite may be forming more or less uniformly along the Oregon and Washington margin, given similar convergence parameters, but stresses applied to the plate may be quite different. Simpler plate geometry (Hyndman and Wang, 1995) and the lack of a deep slab beneath Oregon (Rasmussen and Humphreys, 1988) may result in lower intraslab stresses and fewer earthquakes than in Washington.

The zone of high-amplitude magnetic anomalies continues through southern Oregon (Fig. 1A) and into northern California, but decreases in amplitude south of lat 43°30′N, possibly reflecting the young age of the subducting Gorda plate beneath southern Oregon and California. Onset of eclogitization shifts toward the trench in warmer slabs (Peacock and Wang, 1999), and water may be released before the Gorda plate reaches the upper-mantle wedge, thus reducing the amount of serpentinite produced in the wedge. Temperatures at upper-mantle depths in southern Oregon may also exceed the Curie point of magnetite.

We have examined two other subduction zones in the circum-Pacific for similar relationships. Intraslab earthquakes in southern Alaska from 1988 to 1998 occurred within a well-defined zone (Fig. 4B) located northwest of the trench axis (Ratchkovski and Hansen, 2002). Thermal models of southern Alaska (Oleskevich et al., 1999) indicate that the mantle wedge begins ~300 km from the trench and is significantly cooler than the Curie point of magnetite. The mantle wedge also corresponds with a discontinuous low-velocity zone at and below the Moho depth of 40 km (Zhao et al., 1995). West of long 148°W, the distribution of intraslab earthquakes correlates closely with a high-amplitude positive magnetic anomaly (Fig. 4A) (Saltus et al., 1999) and negative Bouguer gravity anomaly. The magnetic anomaly, the southern Alaska deep magnetic high, corresponds with Jurassic and younger arc-related rocks and basement, but is inferred to have a deep (50 km) component as well (Saltus et al., 1999). The spatial association between this magnetic anomaly, a gravity low, intraslab earthquakes, low-velocity upper mantle, and mantle temperatures below the Curie point of magnetite suggests that part of the anomaly west of long 148°W may originate from the mantle wedge. However, the number of intraslab earthquakes decreases abruptly east of long 146°W, even though the southern Alaska deep magnetic high continues farther eastward. The subducting Pacific plate is thought to be continuous across this seismic boundary, at least in the depth range of 20–45 km (Page et al., 1989). As in Oregon, the eastward decrease in intraslab earthquakes may indicate changing plate stresses due to changes in plate geometry (Brocher et al., 1994).

A large, linear magnetic anomaly along the east coast of northeastern Japan has been interpreted as reflecting the crustal underpinnings of a Cretaceous arc (Finn, 1994). We do not dispute that interpretation but speculate that part of the magnetic anomaly may originate from even deeper depths. As evidence, we note that the anomaly over northeastern Honshu Island is directly above that part of the mantle wedge shown to be cooler than the Curie point of magnetite (Peacock and Wang, 1999) and above a discontinuous low-velocity zone at and below Moho depths (~40 km) (Zhao, 2001).

Along cool subduction zones, such as at southern Alaska, the downdip limit of rupture during megathrust earthquakes may be controlled by the position of the hydrated mantle wedge (Oleskevich et al., 1999; Hyndman et al., 1997). If the rheological properties of serpentinite within the wedge prevent the megathrust from locking over times sufficient to generate great earthquakes, we might expect the locked zone at cool subduction zones to be just updip from high-amplitude magnetic anomalies. As predicted, the landward extent of coseismic slip during the 1964 M_W 9.2 Prince William Sound earthquake (Johnson et al., 1996) corresponds closely with the margin of the southern Alaska deep magnetic high (Fig. 4B).

CONCLUSIONS

The spatial disparity between gravity and magnetic anomalies of the Oregon forearc is consistent with a hydrated mantle wedge observed in seismic reflection data. Along with the well-known gravity signature of subduction zones, it appears that some subduction zones have distinctive magnetic signatures of deep structures and processes. Long-wavelength magnetic anomalies in the absence of corresponding positive gravity anomalies may provide a means to map hydrated mantle in convergent-margin settings.

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