MAP I–1528

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MAP SHOWING WORLD DISTRIBUTION OF CARBON-DIOXIDE SPRINGS AND MAJOR ZONES OF SEISMICITY

By Ivan Barnes, William P. Irwin,
and Donald E. White

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TO ACCOMPANY MAP I–1528

GLOBAL DISTRIBUTION OF CARBON DIOXIDE DISCHARGES AND MAJOR ZONES OF SEISMICITY

By

Ivan Barnes, William P. Irwin, and Donald E. White

ABSTRACT

Carbon-dioxide discharges are concentrated along zones of seismicity such as the circum-Pacific belt and the alpine belt of southern Europe and Asia Minor. They commonly occur along young orogenic belts and are seldom found in either old orogenic belts or cratonal areas of continents except where the cratons are being fragmented. Submarine springs discharging CO_2 are known at only a few localities along oceanic crustal spreading centers, but these may indicate a highly common and widespread phenomenon. Geologic and isotopic data indicate that the CO_2 being discharged from these several tectonic settings is derived variously from (1) organic material, (2) metamorphism of marine carbonate rocks, and (3) the mantle. Production of CO_2 at depth may develop high pore pressure and thus facilitate slippage of faults. Rapid release of CO_2 may result in explosive activity.

INTRODUCTION

Carbon-dioxide (CO_2)-rich waters have long been of interest. As early as 77 A.D., Plinius Secundus (LXXVII, Libra XXI) reported on springs at Tungri, which is the present-day Spa, Belgium (Bostock and Riley, 1856), and on springs at Dorylaei (Plinius Secundus, LXXVII, Libra V), the present-day Eskisehir, Turkey (Bostock and Riley, 1887).

The production of CO_2-rich waters (commonly also rich in boron) by active metamorphism of carbonate-bearing rocks at depth was first suggested by White (1957). Water must be driven off because metamorphism at high temperature generally is accompanied by dehydration. Many rocks undergoing metamorphism contain carbonates and silicates that may react to release CO_2. Organic material may also be a source of CO_2 and hydrocarbon gas. Two fluid phases escape under lithostatic pressure gradients, a water-rich liquid (high in bicarbonate, boron, and other constituents) whose ^{18}O composition is near zero per mil and whose deuterium composition is in the range -30 to -60 per mil, and a CO_2-rich vapor that may contain large amounts of hydrocarbon gases and H_2S. Because the metamorphic gas and water stem from different reactions, they may be generated at the same time or at different times. CO_2 is likely to be the most notable metamorphic constituent in surface effluents, occurring either as CO_2-rich vapor or as anomalously large amounts of bicarbonate dissolved in water. The CO_2 vapor commonly discharges through meteoric water. Metamorphic water is less commonly discharged at the surface as springs. It is recognizable even if somewhat diluted with meteoric water (White, Barnes, and O'Neil, 1973) because the metamorphic water is so anomalous in chemical and isotopic composition (Barnes and others, 1981). The presumed metamorphic water is thought unlikely to be diluted by meteoric water where pressures are lithostatic, because the meteoric waters would have to flow against the gradient; however, dilution probably is extensive at hydrostatic pressures. Mixing of metamorphic and meteoric waters is suspected if the concentration of chloride is high or where contents of bicarbonate and boron are large even though the isotopic composition is similar to that of meteoric water. Metamorphic water in amounts of less than 10 percent may not be detected isotopically in a mixture of metamorphic water and meteoric water.

CO_2 discharges in California were shown to be related to certain lithic provinces and major faults (Barnes, Irwin, and Gibson, 1975). Aseismic movement (creep) along certain segments of the San Andreas fault probably is related to high CO_2 pressures or to structurally diverted CO_2-charged water (Irwin and Barnes, 1975). Recognition of an apparent relation between CO_2 discharges and seismicity led to a preliminary report and map showing the global distribution of the two phenomena (Barnes, Irwin, and White, 1978). Following this early compilation, much additional data regarding the distribution of CO_2 discharges has been obtained, particularly from Afghanistan, China, and Peru. More information on the distribution and isotopic composition of gases emitted from submarine thermal centers has become available.

For our compilation, a CO_2-rich discharge is defined as that of a gas containing more than 90 percent CO_2 by volume by chemical analysis, or as a water that contains at least 1 gram per liter (g/L) dissolved CO_2 or 1 g/L bicarbonate (HCO_3^{-1}) and with a pH less than 8.3. Adsorption of CO_2 from the atmosphere by alkaline waters may be indicated by a pH greater than 8.3. Specifically excluded from this compilation are formation waters from oil fields. Although some of those formation waters are reported to contain more than 1 g/L HCO_3^{-1}, Willey and others (1975) and Carothers and Kharaka (1978) showed much of the alkalinity to result from acetate (CH_3COO^-) and propionate ($CH_3CH_2COO^-$) ions.

DISTRIBUTION OF CO_2

The CO_2 discharges are concentrated in two major areas of the world (see map). One is a narrow circum-Pacific belt that extends for more than 30,000 km from New Zealand through the island chain of eastern Asia, through western North America to South America. The other major concentration is in a broad area in central and southern Europe and Asia Minor. In both areas the geographic coincidence with major zones of historical seismicity is generally striking. Isolated CO_2 discharges also tend to occur in locally seismic areas. Zones of CO_2 occurrences coincide with some orogenic zones containing ultramafic rocks and blueschist-facies rocks, but in old orogenic zones such as the Urals and the Appalachians, CO_2 discharges are generally absent. Equally impressive is the general absence or scarcity of CO_2 discharges and seismicity in Australia (except for the Holocene volcanic field of Victoria) and in most other major old cratonic regions of the world. The similarity in distribution of CO_2 discharges and zones of seismicity suggests that the production of CO_2 is related to fundamental tectonic processes that are operating widely at the present time. Some CO_2 discharges, however, are near young or active volcanoes, and in regions of high heat flow. Submarine discharges of CO_2 have been discovered at a few places along crustal spreading ridges, such as near the Galapagos Islands and at the Loihi Seamount, (Hawaiian Islands), and similar occurrences may be more commonplace than now recognized.

Both the CO_2 discharges and the seismic epicenters are concentrated mainly along or near the boundaries of major crustal plates and probably result from the interaction of the plates. It is along these active plates that the resistance to plate motion is expressed as seismic energy and anomalous temperatures. Where plates are convergent, conditions are appropriate for release of CO_2 from marine carbonate-bearing rocks through processes of subduction, metamorphism, and igneous intrusion. Where plates are divergent as along mid-ocean ridges, the CO_2 escapes from the mantle. In addition, continental fractures extending to sufficient depth may also yield CO_2 from the mantle as along the Rio Grande rift zone, the East African rift zone, and the cratonal rocks of St. Lawrence valley of eastern Canada. Within these tectonically active zones, carbon dioxide is being discharged from rocks as old as Precambrian and as young as Holocene. The generation of CO_2 is a long-term event compared to the historical record of seismicity, and thus may be a useful parameter in regional seismic zoning. In old cratonal regions the general absence of both CO_2 discharges and seismicity indicates the continuance of a long history of tectonic quiescence in those regions. Old cratonic areas may overlie areas of the mantle depleted of carbon dioxide and hence nonconvecting.

ORIGIN OF CO_2

Throughout the world, CO_2 issues from metamorphic rocks as well as from rocks that have no metamorphic history. The CO_2 is thought generally to come from three different sources: (1) organic material, (2) metamorphism of marine carbonate rocks, and (3) the mantle. Stable-isotope data are helpful in identifying the sources of CO_2, especially where there is no evident near-surface source. Organic material, in the form of coal, fossil wood, and petroleum, is rather depleted in ^{13}C (carbon-13); such materials usually contain less than -20 per mil (Craig, 1953). The ^{13}C isotope composition of marine carbonates is approximately 0 per mil relative to the PDB (Peedee belemnite) standard (Craig, 1953). Direct evidence for the isotope composition of CO_2 from mantle sources is provided by inclusions in volcanic rocks erupted along spreading ridges. Moore and others (1977) reported $\delta^{13}C$ values from -4.7 to -0.5 per mil for fluid inclusions in basalt samples from the Pacific Ocean. Pineau and others (1976) reported $\delta^{13}C$ values of -7.6 to 0.5 per mil for CO_2 inclusions in tholeiitic rocks from the mid-Atlantic Ridge. Other situations thought to provide direct evidence of isotopic composition of mantle-derived CO_2 are the discharges at crustal spreading centers and at mantle plumes. Moore and others (1977) reported ^{13}C values of -5.4 and -5.8 per mil for the discharges on the East Pacific Rise and -4.7 per mil for the $\delta^{13}C$ composition of CO_2 from the Cayman trough. CO_2 issuing from the Loihi Seamount has a $\delta^{13}C$ value of -4.8 per mil (J. G. Moore, oral commun., 1981). Thus, $\delta^{13}C$ for mantle-derived CO_2 is evidently in or near the range of -4.7 to -8.0 per mil.

Even where CO_2 is discharged from or near young volcanoes, the stable-isotope composition may be useful to verify the source of the CO_2. Many volcanic deposits rest on marine sediments. Where volcanoes are on marine sediments, isotopic compositions of carbon may show whether the CO_2 originates where the melt originates or whether it is produced during metamorphism of the sediments. CO_2 may also be of metamorphic origin, stemming from either regional metamorphism or from a local high-temperature environment from a direct reaction of silicate melts with sedimentary rocks. The CO_2 from sedimentary rocks may come from either organic material or carbonate minerals. Low-greenschist-facies metamorphism of the graywackes of New Zealand (Giggenbach, 1982) and California (Barnes and others, 1973) yields both carbon dioxide and methane. Higher grade metamorphism, as in central and southern Europe, yields only carbon dioxide because any kerogen remaining has been depleted of hydrogen. Still another source of CO_2 may be degassing of the mantle, which may or may not be accompanied by eruptions of mantle-derived silicates. Surficial discharge of CO_2 from complex environments may be derived from a combination of these sources.

An example of the use of isotopic compositions to determine the source of the CO_2 is a study of the carbon dioxide discharging from the Bohemian Massif at Karlovy Vary, Czechoslovakia. There the bedrock is Variscan granite, which is a singularly poor source for either the CO_2 or the calcite that forms extensive travertine deposits. The isotopic composition of the CO_2, near 0 per mil, strongly suggests that the source of CO_2 is marine carbonate-bearing rocks that must underlie the Bohemian Massif (Barnes and O'Neil, 1976).

High thermal gradients tend to coincide with CO_2 discharges, but more than merely high temperature is required to generate CO_2. Simple thermal decomposition of calcite yields lime (CaO), an uncommon mineral (Barnes and others, 1982). Silica and other oxides are required to form metamorphic calcium minerals. The CO_2 found discharging is a product of a chemical reaction.

Metamorphism to produce CO_2 may occur under a large variety of physical and chemical conditions, and the various conditions will be identified as more detailed studies are made. As an excellent example of the detailed studies needed, Muffler and White (1968, 1969) have described the metamorphic conditions in clastic sediments of the Salton Sea area of California. The sediments are in part detrital calcite and dolomite from marine carbonate rocks of the Colorado Plateau. The calcite and dolomite have $\delta^{13}C$ contents that average -2 per mil. Dolomite reacts at temperatures as low as 180°C, and where the produced CO_2 can escape, calcite is lost near 300°C. Incomplete decarbonation at depths below 1,000 m and temperatures above 250°C (Clayton and others, 1968) tends to produce CO_2 in which the $\delta^{13}C$ content ranges from -3 to -5 per mil, suggesting that ^{13}C is selectively concentrated in escaping fluids.

There are only two requirements for a chemical reaction to take place, a decrease in chemical potential and a reaction path or mechanism. As long as a negative chemical potential and a reaction path exist for calcite to react to form another calcic mineral and CO_2, the reaction will occur. The reaction may be localized as in contact metamorphism or may be dispersed as in regional metamorphism.

Craig (1963) reviewed the complexities and uncertainties of interpretation of ^{13}C data in geothermal areas. In the absence of other information, ^{13}C compositions near 0 per mil should be regarded conservatively as being from a marine carbonate source. Fractionations during solution and exsolution added to the range of marine carbonate ^{13}C compositions can probably yield a range in $\delta^{13}CO_2$ values from -5 to +5 per mil.

The production of a separate CO_2 phase in the rocks may have structural implications. As Lockner and Byerlee (1977) have shown experimentally, high pore pressure markedly reduces the strength of rocks, and if the least principal stress is vertical, thrust faulting may occur. Hubbert and Rubey (1959) pointed out the role high fluid pressures play in thrust faulting. The importance of high fluid pressures in the tectonics of the California Coast Ranges was described by Berry (1973). Although these authors considered water alone to be the principal agent, CO_2 as a separate phase would be just as effective in forming and transmitting high fluid pressure.

MAP COMPILATION

The chemical criteria for the CO_2 discharges are arbitrary, but during the course of the compilation it became obvious that changing the concentration limits to values as low as 0.5 g/L (still an unusually high HCO_3^- concentration) would serve no purpose other than to provide more occurrences from the same general areas already established and would not change the general pattern of occurrences. The sources of data for the CO_2 discharges are given separately from the references cited in the text. For uniformity all sources of data have been translated into English. The authors would appreciate receiving additional information on the location and the chemical and isotopic composition of CO_2-rich waters.

The CO_2 occurrences and the major zones of seismicity are compiled on a base map that shows the global distribution of alpine-type ultramafic rocks and blueschists (Irwin and Coleman, 1972). Additional blueschist localities are from N. L. Dobretsov (written commun., 1973). It should be noted that the zones of seismicity are generalized from Tarr (1974), with the exception of data from Fairhead and Henderson (1977) for Africa, Lee and others (1978) for China, and NOAA (1970) for the north polar region. Tarr's (1974) map shows only magnitude-5 and greater earthquakes and is restricted to the period 1963-72. A more inclusive and lengthy record of seismicity would show an even closer correlation with the CO_2 discharges.

CIRCUM-PACIFIC BELT

A roughly continuous belt of CO_2 discharges, more than 30,000 km long, stretches from southern South America through Central America, western North America, Kamchatka, Japan, Taiwan, and New Guinea to New Zealand along the circum-Pacific belt.

In the Matsushiro area of Japan, CO_2 discharges associated with earthquakes have been documented by Yoshioka and others (1970). In the same area, Wakita and others (written commun., 1977) reported $\delta^{13}C$ values from -1 to -3 per mil and interpreted the source of the CO_2 to be Paleozoic marine carbonates. Wakita and others attributed the high value of 8.9 X 10^{-6} for the $^3He/^4He$ ratio for the He in the CO_2 to a mantle-derived source. They interpret the He to be derived from a small intrusion into the crust accompanied by reactions with marine carbonates to yield CO_2.

On the Alaska Peninsula at Gas Rocks (57°51'40" N., 156°30'00" W.), an explosive volcanic episode began in April 1977 that yielded an alkali olivine melt inferred to have come from the mantle (Kienle and others, 1980). In August 1977 the copious gas discharge near Gas Rocks was sampled. The gas was 98 percent CO_2 and its ^{13}C composition -6.36 per mil (Barnes and McCoy, 1979). The content of ^{13}C is too low for a marine-carbonate source but is in the range of values for CO_2 from the mantle. The explosive eruption at Gas Rocks is probably due to an abrupt release of CO_2 from a magma chamber in which the pressure of CO_2 dissolved in the melt exceeded the total confining pressure.

The broad belt of CO_2 occurrences of the Western United States may be subdivided into three subsidiary belts: (1) a coastal (Franciscan Complex) geochemical province, (2) the Sierra Nevada, and (3) the Rocky Mountains.

Franciscan rocks of the coastal geochemical province discharge CO_2 (Barnes, 1970) generally accompanied by methane (Barnes and others, 1973). A current study shows that CO_2 from Franciscan rocks has $\delta^{13}C$ values that range from +5.2 to -14.0 per mil. The data at hand show no relation between the ^{13}C data and the existence of travertine deposits or the presence of methane in the gases. The CO_2 is apparently generated both by the breakdown of organic material depleted in ^{13}C and by solution or metamorphism of calcite of marine origin enriched in ^{13}C. If the mantle also contributes to the CO_2 flux, its contribution is masked by mixtures of CO_2 from other sources. The present phase of metamorphism of the Mesozoic eugeosynclinal sedimentary rocks of the Coast Ranges of California is probably in its early stages, even though the rocks were previously metamorphosed. Labile organic materials are still present and decomposing. The metamorphism is also accompanied by quite high heat flow.

CO_2 discharges from localities in the Sierra Nevada show $\delta^{13}C$ values of -6 to -10 per mil (Barnes and others, 1981). Chemical and isotopic evidence indicates that the fluids are meteoric water that contains CO_2 from the mantle. In order for CO_2 to escape, it must be present as a separate phase in the mantle, and it must exist as a separate phase to at least as shallow a depth as the meteoric water circulates. To be present as a separate phase, the CO_2 pressure must at least equal total (confining) pressure.

In the Rocky Mountains province in Colorado, CO_2 species in CO_2-rich springs have been analyzed for ^{13}C (Presser and others, 1981). The $\delta^{13}C$-enriched CO_2 (-2.0 per mil) found at Rico may be from the metamorphism of shaly limestone and limy shale that were described by McKnight (1974), or from deeper sources. Impure marble that is part of a Precambrian metamorphic complex occurs near Guffey (D. S. Sheridan, oral commun., 1977). The $\delta^{13}C$ value of -1.4 per mil in the CO_2 discharging near Guffey may be from the metamorphism of the marble. CO_2 discharges from the Precambrian Pikes Peak Granite at Manitou Springs (-3.3 to -2.8 per mil) possibly are from a mantle source. If so, mantle-derived CO_2 may be more enriched in $^{13}CO_2$ than indicated earlier. ^{13}C data from complex igneous and metamorphic terranes cannot be unequivocally interpreted without detailed geologic study and consideration of multiple origins.

Yellowstone National Park, Wyoming, is a region that includes several localities of CO_2 discharge and is also noted for extraordinarily high heat flow (Fournier and others, 1976). The two phenomena do not always coincide perfectly, however. For example, heat flow in excess of 2 heat-flow units, or at least 30 percent above the world's average conductive heat flow, characterizes most of the broad central and eastern part of the United States seismic belt (Diment and others, 1975, plate 1), but CO_2 occurrences are no more abundant there than in adjacent areas to the east and north. Conductive heat flow is slow relative to fluid flow. Thus a thermal anomaly at depth may be a source of CO_2 that is discharged at the surface before an increase in heat flux at the surface is noted.

Craig (1961) reported isotope analyses on the CO_2 from Yellowstone National Park in which $\delta^{13}C$ ranges from -1 to -6 per mil and averages (13 samples) -2.8 per mil. Thus, although the average isotope composition is rather close to what would be expected for an average marine limestone, considerable volcanic or mantle CO_2 may be present. Friedman (1970) studied travertine that is presently forming in Yellowstone National Park and reported that fractionations between dissolved carbon species and travertine range from near equilibrium (4 per mil) at 75°C to a disequilibrium fractionation of only 1 per mil at 25°C. Neither Craig nor Friedman, however, measured the isotope fractionation between dissolved CO_2 species and CO_2(gas). In the Sierra Nevada and Klamath Mountains of California, Barnes and others (1981) studied the fractionation between dissolved CO_2 species and CO_2(gas) from the springs. They found that fractionations range from equilibrium (4 per mil) down to no fractionation (0 per mil) over the temperature range 8°C to 43°C. These relatively small fractionations permit the source of the Yellowstone CO_2 gases to be identified as limestone (Craig, 1953), and led Friedman (1970) to conclude that dissolved CO_2 species and travertine of Yellowstone National Park are derived from marine limestone by decarbonation. Similarity of lead isotopes in the limestone and travertine also points to the limestone as the source for the travertine (Leeman and others, 1977).

Studies of gases and waters near and in Mount St. Helens show that the volcano is full of steam (85 percent) and other gases, chiefly CO_2 (Evans, Banks and White, 1981). The steam is from metamorphic brine in the underlying Tertiary Ohanapecosh Formation (Barnes and others, 1981). Prior to the May 18, 1980 eruption, CO_2 with $\delta^{13}C$ values of -19 per mil issued from the volcano; after the eruption, however, values of -10 to -11 per mil were found as the proportion of mantle-derived CO_2 exceeded that from the breakdown of organic material.

In summary, the scattered CO_2 discharges of the circum-Pacific belt seem generally to be derived from metamorphism of carbonate-bearing rocks and from mantle sources. Some widely separated occurrences may be related to isolated intrusions that have caused contact metamorphism.

EUROPE AND ASIA MINOR

The CO_2 that is discharging from localities in Europe and Asia Minor is derived in large part from metamorphism of marine carbonates, whether from originally impure limestone or from calcareous siliceous sediments. A marine carbonate origin for the CO_2 of the mineral waters of Czechoslovakia was suggested by Barnes and O'Neil (1976) on the ground that $\delta^{13}C$ values of the high-CO_2 waters are close to 0 per mil. The CO_2-rich waters discharging in Czechoslovakia show deuterium and ^{18}O compositions (Barnes and O'Neil, 1976) that are in excellent agreement with the stable-isotope relations of meteoric water (Craig, 1961). The isotopic results confirm the conclusions of Kacura and others (1969), based on hydrogeologic analysis, that the water is meteoric. Dowgiallo and others (1973, 1975) showed that much of the CO_2 from Polish mineral waters probably derives from oxidation of organic matter. The ^{13}C data of Buachidze and Buachidze (1976) show an average value near 0 per mil and indicate that the CO_2 of the Caucasus is probably also derived from marine carbonates. Cornides and Kecskes (1974) concluded from ^{13}C data that the CO_2 of Hungarian mineral waters was derived partly from metamorphism of limestone and partly from volcanic sources. By measurements of the isotopic compositions of French mineral springs, Batard and others (1982) showed that the water is of meteoric origin but the CO_2 is largely of igneous (mantle?) origin. In a thorough study of the isotopic compositions of CO_2 in central and southern Italy, Panichi and Tongiorgi (1976) showed that most of the CO_2 is from metamorphism of marine carbonates. Their isotopic data agree with the results separately reported by Manfra and others (1974). Craig (1963) showed that the waters from Lardarello, Italy, are also chiefly of meteoric origin, but with enrichments in ^{18}O owing to reaction (exchange) with the rocks.

The lack of identified metamorphic or magmatic water accompanying the CO_2 is puzzling. Possibly water that was present earlier either has escaped or has been incorporated in hydrous minerals. Conceivably, metamorphic water does not reach the surface because after it condenses it is no longer buoyant, or, if it escapes, it may be diluted beyond recognition by meteoric water, as in the Sierra Nevada, Calif. (Barnes and others, 1981). The observation of large-scale exchange of ^{18}O between igneous rocks and meteoric waters (Taylor, 1974; Margaritz and Taylor, 1976) is consistent with the failure to find metamorphic water in Europe or Asia Minor.

In Europe, the belts of CO_2 discharge correlate approximately with high heat flow, not only in the Precambrian basin of central Europe but also to the east and west. The high heat flow in the Caucasus and the Crimea (Petkov and others, 1976) corresponds quite well with the occurrence of CO_2 discharges. To account for the high heat flow of the Pannonian Basin, Stegena and others (1975) advocate mantle-derived intrusion into the overlying sediments. They stated that the high heat flow cannot be supported by thermal conduction. Lachenbruch and others (1976) pointed out that intrusion is not as effective in transferring heat as convective flow in a melt. However, once the melt stops convecting, heat flow decreases until a more normal thermal gradient is established. Convective heat flow and the long subsequent time necessary for recovery may explain why older metamorphic terranes such as the Appalachians and the Urals show so little evidence of fluids derived from present-day metamorphism. Saratoga Springs, New York, is the only discharge of CO_2 known in the Appalachians, and none is known in the Urals.

Further evidence for metamorphic reactions in the Roman province was supplied by Hurley and others (1966). On the basis of the $^{87}Sr/^{86}Sr$ ratios and the Rb and Sr contents of potash-rich lavas, they concluded that the lavas are derived from the melting of old sialic crustal rocks. Turi and Taylor (1976) concluded from ^{18}O compositions that the volcanic rocks of the Roman province have undergone moderate to extensive reactions with crustal material, but are at least in part derived from the mantle.

CONCLUSIONS

Regional metamorphism, perhaps in early stages, is probably occurring now in California in eugeosynclinal rocks and their attendant ultramafic rocks. Regional metamorphism, perhaps of a more advanced stage, is occurring in Europe and Asia Minor, where the CO_2 production is principally from the breakdown of calcite of marine origin. Older terranes such as the Appalachian and Ural orogenic belts may be products of metamorphism of the type now occurring in Europe and Asia Minor.

Relatively isolated metamorphism may be occurring within a belt from South America to New Zealand, perhaps related to contact metamorphism associated with intrusions. The areal extent of CO_2 production in Europe and Asia Minor is much greater than that in any area found along the circum-Pacific belt with the possible exception of the Western United States. Judging from the CO_2 occurrences, if any areas of the world are undergoing regional metamorpism at the present time, they are the orogenic belts of Europe and Asia Minor and the Coast Ranges of California. Many of the rocks that are being metamorphosed have already undergone metamorphism one or more times.

Crustal spreading centers are also the loci of CO_2 discharges, and the isotopic composition of their discharges is thought to indicate mantle origin. Discharges of CO_2 from volcanic centers are sometimes accompanied by seismicity and eruption of lava, and at other times the discharges are aseismic and consist only of gas. It is unlikely that the aseismic discharge of gas is caused by upward movement of magma to lesser depths where degassing occurs. More likely, it is caused by degassing of the mantle, which perforce must contain a separate CO_2 phase in addition to the silicates.

At no pressure or temperature is CO_2 as dense as the silicate minerals that make up the mantle (Kennedy and Holzer, 1966), and volumes of mantle that contain CO_2 must therefore be buoyant. The buoyancy provides a mechanism for upward movement of magma which, being CO_2 saturated, will degas as pressure decreases. Thus, the CO_2 is both a causal agent of the upward movement of magma and a product of the degassing that results from the upward movement.

The occurrence of CO_2 discharges along crustal spreading centers may also indicate a causal relation in that the buoyancy of gas-charged melts may well be responsible for mantle convection and resulting seafloor spreading.

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