1. Introduction

1.1. Previous research on weathering and weathering rates

Weathering plays a major role in the denudation of land surfaces. Disintegration and decomposition of various kinds of hard bedrock facilitate the erosion of the land surface by several kinds of external agencies such as running water, waves, wind and glacier. Therefore, studies on weathering processes and their influence on changing properties of landform materials are important in the field of geomorphology.

Weathering has been conventionally classified into three types: (1) physical weathering (mechanical weathering), (2) chemical weathering, and (3) biological weathering. Although these three types of weathering often operate simultaneously, many textbooks on weathering or geomorphology distinguish the three weathering processes (*e.g.*, Strahler and Strahler, 1978; Yatsu, 1988; Selby, 1993). Selby (1993) classified the physical processes of weathering into pressure release, thermal expansion, crystal growth (frost action and salt weathering), wet-dry slaking, fatigue failure and stress corrosion. Selby (1993) also recognized that chemical weathering processes include solution, hydration, hydrolysis and secondary mineral formation. Besides these processes, oxidation and carbonic acid action also belong to the chemical weathering processes (Strahler and Strahler, 1978). Selby (1993) regarded biotic weathering as a combination of chemical and physical weathering effects such as: (1) rock disintegration by the action of roots and burrowing animals; (2) transfer of material by animals; (3) increasing CO_2 released by respiration; and (4) complex chemical effects such as chelation.

Matsukura (1994) classified weathering researches into three types: (1) weathering processes, (2) properties of weathering products, and (3) weathering rates. Extensive literature on weathering processes has been accumulated through laboratory experiments on chemical weathering (*e.g.*, Berner, *et al.*, 1980; Lasaga (1984) ; Grandstaff (1986); Tamari *et al.*, 1988; Hirose *et al.*, 1995; Takaya *et al.*, 1996) and those on physical weathering (*e.g.*, Cooke and Smalley, 1968; Aires-Barros *et al.*, 1975; Matsukura and Yatsu, 1982; McGreevy and Smith, 1982, 1984; Tharp, 1987). Most of the experimental approach, however, is adequate to monitor short-term weathering processes. It generally takes much longer time before weathering leads to rock disintegration and subsequent accelerated erosion. Therefore, long-term weathering processes and their relation to geomorphic processes need to be discussed using weathering products observed in the field. For this purpose, Lumb (1962), Deere and Patton (1971), Suzuki *et al.* (1977) and Matsukura *et al.* (1983) studied the vertical changes in rock properties of weathered granite exposures from grus near the land surface to less weathered bedrock. Oguchi *et al.* (1994) and Oguchi and Matsukura (1996) also analyzed weathered rhyolite rocks erupted in different ages to discuss weathering processes responsible for the reduction of rock strength. Weathering products produced from dated rocks can also be used to estimate long-term weathering rates. Nevertheless, studies on materials subjected to long-term weathering are still limited in number, although their importance in geomorphological research has been stressed. So far the works on weathering profile such as Suzuki *et al.* (1977) have not intended to estimate long-term weathering periods because of the difficulty in time estimation.

The meaning of the term "weathering rate" is slightly different among researchers (Matsuskura 1994). The term has often been used as a synonym of the chemical denudation rate (*e.g.*, Waylen, 1979; High and Hanna, 1970; Trudgill, 1975, 1976 and Trudgill *et al.*, 1981; Crabtree and Trudgill, 1985; Hirose *et al.*, 1994 and 1995). The term also represents the formation rates of weathering products which include soils and clay minerals (*e.g.*, Alexander, 1985; Wakatsuki and Rasydin, 1992; Garrels and Mackenzie, 1967; Yoshioka, 1975; Suzuki and Hachinohe, 1995), dated materials such as volcanic ash (*e.g.*, Hay, 1960; Leneuf and Aubert, 1960; Trendall, 1962; Ruxton, 1968;

Haantjens and Bleeker, 1970; Menard, 1974; Nahon and Lapportient, 1977; Amit *et al.*, 1993), and thin weathered zones of rocks such as weathering rinds, rock varnish and hydration layers of obsidian artifacts (*e.g.*, Friedman and Smith, 1960; Friedman and Long 1976; Katsui and Kondo, 1965). Another usage of the term is the changing rates of rock properties with weathering. Kimiya (1975a, 1975b) and Crook and Gillespie (1986) investigated fluvial-terrace gravel of different ages and concluded that rock strength decrease exponentially with increasing weathering time. Oguchi *et al.* (1994) also pointed out that both compressive and tensile strengths declined drastically in the early stage of weathering. Such changes in rock strength are crucial to discuss the effects of weathering on geomorphic processes. However, studies on the changing rates of rock properties have been limited in number.

Analyses of various properties of weathering products are also important because weathering progresses with simultaneous changes in several rock properties. For example, chemical changes often result in the reduction of rock strength (Matsukura *et al.*, 1983; Oguchi and Matsukura, 1996). In order to discuss their relations, both chemical and mechanical properties should be analyzed. Most of the previous studies on weathering, however, dealt with only changing in chemical and/or mineralogical properties (*e.g.*, Craig and Loughnan, 1969; Singer, 1984; Chesworth, *et al*, 1981). So far a limited number of research (Saito *et al.*, 1974; Eggleton, 1987; Waragai, 1993; Oguchi *et al.*, 1994) has investigated chemical and/or mineralogical properties along with mechanical and/or physical properties.

1.2. Previous research on weathering rinds

Weathering rinds developed on rocks are useful for weathering study because very detailed investigation can be performed on the rinds with small areal extent. Moreover, the changing rates of rock properties due to long-term weathering can be estimated using the weathering rinds of rocks in dated deposits. The studies of weathering rinds, however, have often been confined to the estimation of the ages of Quaternary deposits. Cernohouz and Šolc (1966) first proposed that the relationship between weathering-rind thickness and formative time is expressed by a logarithmic function. Absolute-age functions can be determined if some of the deposits with weathering rinds are dated using other methods such as ^{14}C measurements. If the function is given, ages of landforms can be calculated by substituting measured weathering-rind thickness into the equation. This method has often been applied to glacial deposits in high mountains (*e.g.*, Birkeland, 1973; Porter (1975); Burke and Birkeland, 1979; Anderson and Anderson, 1981; Chinn, 1981; Colman, 1981a, 1981b, 1982; Colman and Pierce, 1981; Whitehouse *et al.*, 1986; Knuepfer, 1988; Shiraiwa and Watanabe, 1991; Koizumi and Seki, 1992; Koizumi and Aoyagi, 1993; Aoki, 1994). A few studies have investigated not only thickness but also the other properties of weathering rinds. Colman (1981a; 1982) analyzed the chemical and mineralogical properties of weathering rinds developed on glacial deposits. Kuchitsu (1990) identified the minerals of weathering rinds formed on lithic artifacts. Matsukura *et al.* (1994a, 1994b) and Oguchi *et al.* (1995) studied mineralogical, chemical, and mechanical properties as well as colours of weathering rinds on andesite gravel altered by volcanic gases. However, more systematic studies based on concurrent investigation of several rock properties are needed to establish a model for the formation of weathering rinds. Moreover, the relationship between weathering-rind properties and weathering time remains to be determined.

Previous definition of the weathering rind also has the following problems. The first problem is that weathering rinds often consist of sub-zones with different colours. General criteria to correlate weathered zones with rock colour have not been established. Therefore, if the rind consists of zones with different colours, the thickness of weathering rind may differ among researchers. The second problem is that the zone with a certain colour near the rock surface may not strictly correspond to the zone subjected to weathering. For example, porous rocks are often subjected to "deep weathering" which can alter rock properties of inner zones. Consequently, systematic investigations of weathering rinds and inner zones are needed not only for the improved understanding of rock weathering, but also for the re-evaluation of dating methods using weathering-rind thickness.

1.3. The purpose of the present study

The review of the previous researches on weathering and weathering rinds indicates that the mechanism of weathering-rind formation has not been well understood, although many researchers investigated the thickness of the rinds. In addition, more studies are needed to explain the actual complex weathering processes occurred in the field. In order to solve the mechanism and rates of weathering-rind formation, this paper investigates andesite gravel with weathering rinds taken from dated fluvial-terrace deposits in the Nasu area, Japan. The rates of long-term weathering are also examined based on the assumption that weathering period is equal to the time between the age of terrace formation (*i.e.*, the age of emergence) and the present. The following two types of weathering rates are investigated: (1) temporal changes in rock properties and (2) growth rates of weathering-rind thickness.

The following procedures were adopted in the present study. Various properties of terrace gravel with weathering rinds are collected as basic data: colours, thickness of the rinds, mineralogy, chemistry, pore-size distribution, bulk density, porosity and Vickers microhardness. Using these data, the relationships between rock properties and weathered depth and those between rock properties and time are examined to discuss the mechanism of weathering-rind development. Finally, a model is proposed to represent the growth rate of weathering rinds.