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Constraints on alluvial clay mineral assemblages in semiarid regions. The Souss Wadi Basin (Morocco, Northwestern Africa)

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ABSTRACT

Illite, chlorite and kaolinite, resulting directly from substratum weathering, dominate the clay assemblages recorded in altered rocks and soils of the Souss Wadi watershed. Nevertheless, the transformation and neoformation of diverse clay minerals, which is mainly controlled by changing climatic, lithological and topographic conditions, enables one to establish three distinctive source areas. High altitude, largely watered zones where chlorite is transformed into vermiculite; middle altitude drier areas where more pronounced seasonal contrast induces the transformation of chlorite into chlorite-smectite mixed layer; finally, semiarid low altitude zones with gentle slopes where the weathering of carbonate-dominated substrata, evaporation and chemical concentration result in smectite and palygorskite neoformation. These minerals, which result from transformation and neoformation, provide suitable environmental indicators and local to zonal tracers of sediment contribution. Nevertheless, the original clay mineral assemblages undergo a significant homogenisation due to the destruction of most of the transformed and neoformed minerals during fluvial transport. As a consequence, inherited clay minerals (illite, chlorite and kaolinite) usually dominate the assemblages recorded in the downstream alluvial sediments. The clay assemblages recorded in different tributary wadi alluvial deposits reflect major sediment contribution from the High-Atlas and the older alluvial plain deposits affected by intensive erosion. On the other side, Anti-Atlas contribution is lesser as a consequence of its wide tableland topography and the widespread outcropping of karstified carbonate rocks, which enhance water infiltration and preclude sediment supply.

KEYWORDS **Clay minerals. Erosion. Semiarid climate. Souss Wadi.**

INTRODUCTION

Understanding of erosion and river transport processes is essential for management of watersheds (i.e. dam building) and also for characterising and quantifying the amount of solid materials shed into the ocean. Many techniques have been developed to achieve this aim: total suspended solid measurement; experimental parcels, SIG and ^{137}Cs techniques (Heusch and Millies-Lacroix, 1971; Lahlou, 1982, 2000; Probst and Amiotte Suchet, 1992; Mabit et al., 1998; Queralt et al., 2000). This paper deals with the use of clay minerals as sedimentary tracers and to characterise erosion and sediment contribution in semiarid zones. Clay mineral genesis is controlled mainly by environmental factors (climate, geology and relief). As a consequence, the analysis of the distribution of clay mineral assemblages, both in river flow suspended particles and the basin catchment, enables one to identify the source areas of these particles. The Souss Wadi watershed was chosen for this study because this river basin is well individualised and its source areas present significant morphological, climatic and geological contrasts, which are essential features to subdivide the drainage area into several distinct contributing zones.

CHARACTERISTICS OF THE STUDY AREA

The Souss Wadi basin extends from 30° to 31° north latitude and from 9°30' to 7°30' west longitude. This river basin stretches approximately 200 km from the Siroua region (western and central Anti Atlas) as far as the Atlantic Ocean and is one of the main hydrological basins of Western Morocco with 16000 km^2 of areal extent (Fig.1). A variety of rocks crop out in the Souss watershed (Fig. 2), whereas the relief is characterised by a relatively flat, alluvial plain in the central portion of the river basin. This low-lying zone is surrounded by steep and high altitude mountains, i.e. the High Atlas to the North and the Anti-Atlas to the South, both exerting a major influence on precipitation (Fig. 3).

Geological setting

Two main structural zones constitute the Souss Wadi basin: the Precambrian western and central Anti-Atlas and the Palaeozoic and Mesozoic western High-Atlas. Both chains are separated by the so-called southern Atlasic fault (Fig. 2). Igneous and metamorphic rocks crop out in the western and central Anti-Atlas (Siroua region) as well as major carbonate units, which make up significant tableland relief. Precambrian volcanic rocks, Palaeozoic shales and sandstones and Permo-Triassic sandstones and mudstones overlie the High-Atlas basement (Argana corridor; Piqué, 1994). A Cretaceous-Eocene succession, which is structured as an east-west trending syncline, crops out on the piedmont of the High-Atlas and as some hillocks in the Souss plain (Figs. 2 and 4B). Thick Pliocene and Quaternary deposits overly this Cretaceous-Eocene succession, including significant fluvial-lacustrine sequences (Souss Formation; Ambroggi, 1963), which are overlain by coarse grained, often carbonate encrusted alluvial deposits (Bhiry et al., 1989).

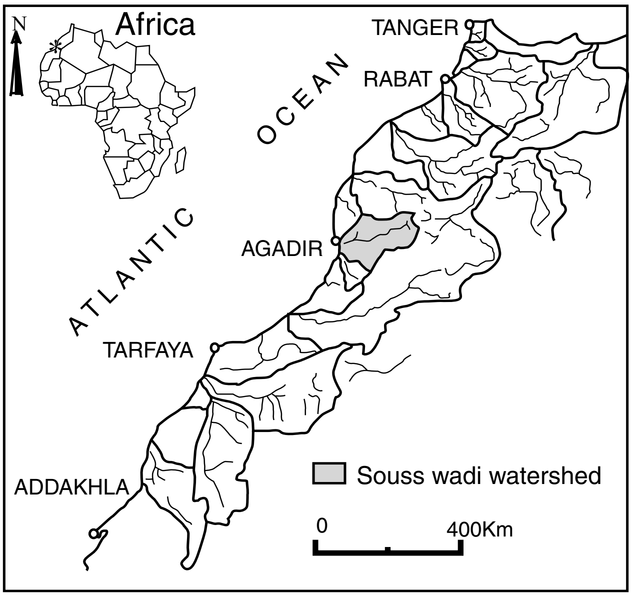

FIGURE 1 | **Principal hydrographic basins of Morocco and neighboring areas showing the location of study area.**

Climate and vegetation

Three factors determine the climate in the Souss region: the high mountains which surround the area, except to the west; the opening of the region to the Atlantic Ocean; and its location at a relatively low, Saharan latitude (Figs. 1 and 3A). The map of precipitation established by Dijon (1969) in comparison to current national meteorological data (Saidi, 1995) shows that the rain intensity in this region depends mainly on altitude (Fig. 3B). This precipitation ranges from less than 300 mm/y in the plain to more than 500 mm/y toward the High-Atlas and Siroua summits. The temperature ranges depend on the altitude, the distance from the ocean and the relief. Thus, internal plains and dry valleys have the highest annual thermal amplitude. The latter decreases toward the ocean and the high altitudes (Table 1). The annual average evaporation varies between 2256 mm in Aoulouz and 1896 mm in Taroudant (Fig. 3).

The most widespread tree species in the basin is *Argania spinosa,* which is very scattered on a large part of the Souss plain, in Anti and High Atlas and in Siroua piedmonts. Moreover, *Tetraclinis* plantations characterise the

TABLE 1 | **Annual thermal amplitude in Souss watershed between 1950 and 1985.**

Stations	Annual thermal amplitude (°C)
Agadir (coastal zone)	10
Argana (dry valley)	20
Taroudant (internal plain)	17
Irhrem (high altitude)	14
Tizi-n-Test (high altitude)	14

Based on data of the National Meteorological Service of Morocco. See localities in Fig. 3.

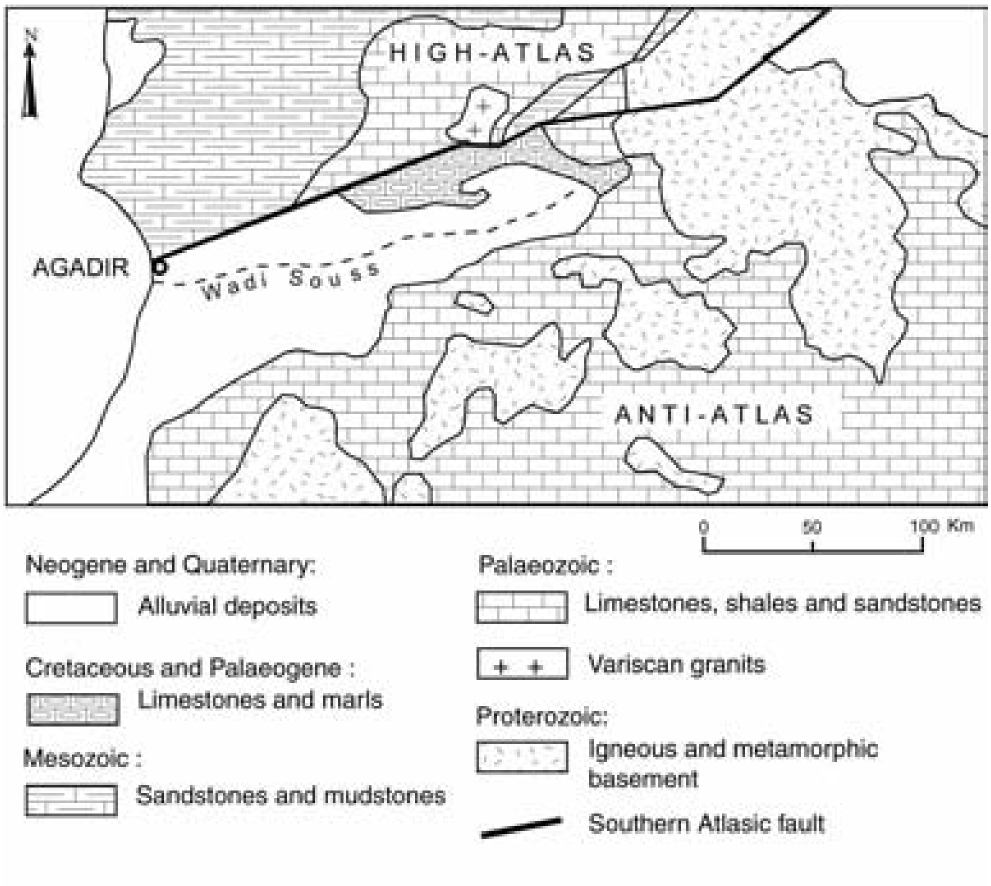

FIGURE 2 | **Geological sketch of the Souss region.**

semiarid mountainous level. A *Juniperus* - *Quercus* assemblage characterises the sub-humid to humid zones located from about 1500 to 2500 m above sea level.

Hydrological framework

The Souss watershed is drained by the Souss Wadi, which is the main river basin collector. The inventory of the different tributaries enables to distinguish four hydromorphological subsections (Combe and Elhebil, 1977): (a) the Souss high basin that is totally collected by the Aoulouz gorges; (b) High-Atlas tributaries, which are the major suppliers of surface water; (c) Anti-Atlas tributaries, with lesser hydrological importance since only Arrhene and Tangarfa wadies reach the Souss river during floods, and (d) Souss mean valley, spreading from Aoulouz to the ocean (Fig. 4).

The Souss Wadi flow is closely related to the rain fluctuations and, as a consequence, shows a remarkable interannual variation, seasonal regime from year to year. Both extreme floods and very marked low water situations are frequent. According to statistics of the Agadir Hydraulic department (DRH), the annual average runoff varies in time and space (Chakir, 1997; Table 2).

The characteristics of the Souss Wadi floods change from year to year, but in general the water discharge and rise is dramatically strong and flashy (Table 3), water flow speed is fast and its solid load is considerable. The total suspended solid (TSS) measured in Ait-Melloul is about 1.6. 10^6 t / yr (Figs. 3 and 4). If we considered the High-Atlas as main supplier of alluvial material the spe-

TABLE 2 | **Discharge variation (m^3/s) in Souss wadi between 1962 and 1983.**

Years (1962-83)	Aoulouz	Taroudant	Ait Melloul
Average discharge	6.78	4.31	9.55
Wet period (1962 - 71)	11.09	9.01	16.49
Dry period (1971 – 83)	3.55	1.02	4.34

Based on data of the Hydraulic department of Agadir.
See localities in Fig. 3.

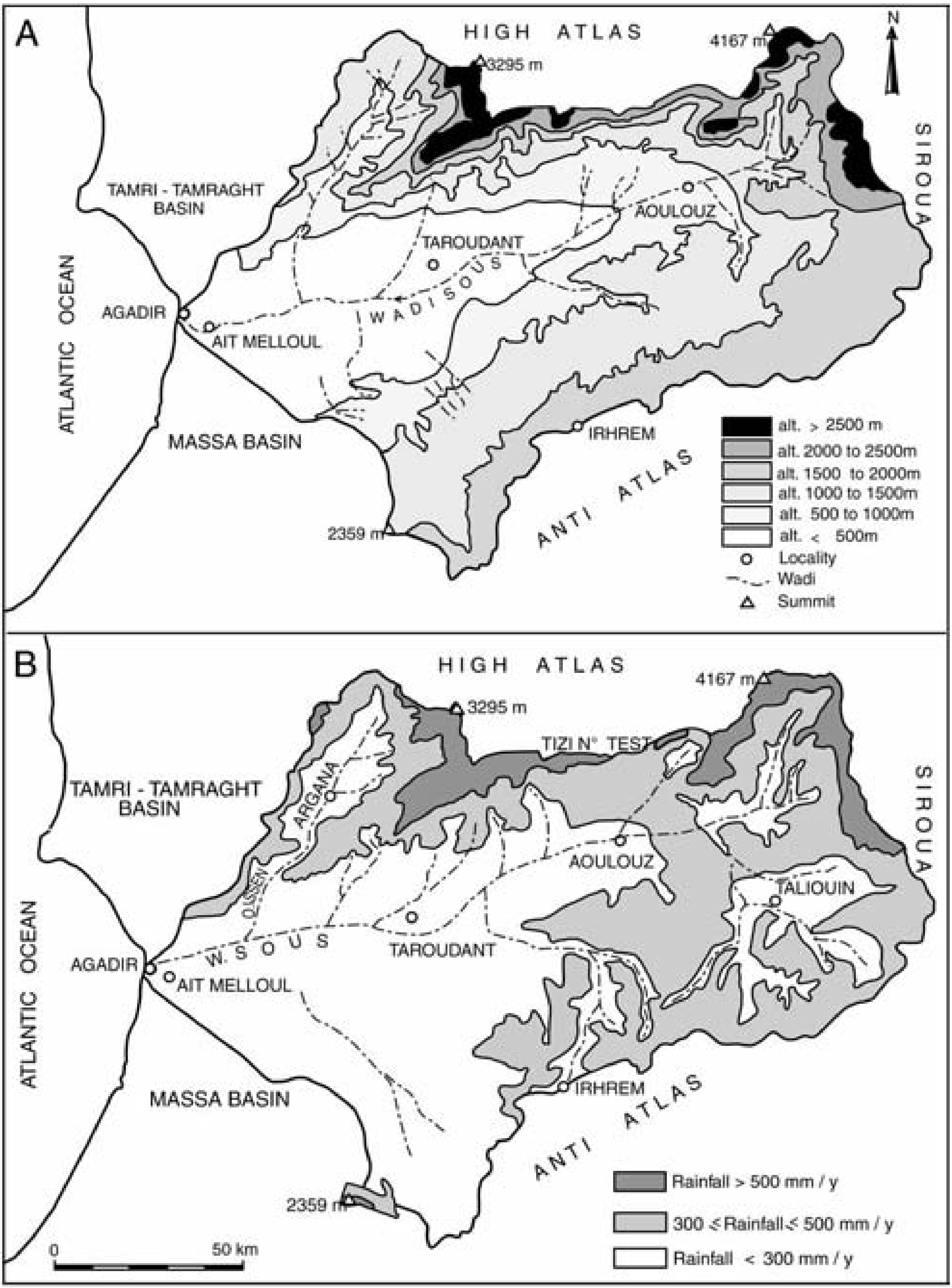

FIGURE 3 **A) Orographic map of Souss Wadi basin. B) Rainfall distribution in the Souss Wadi basin.**

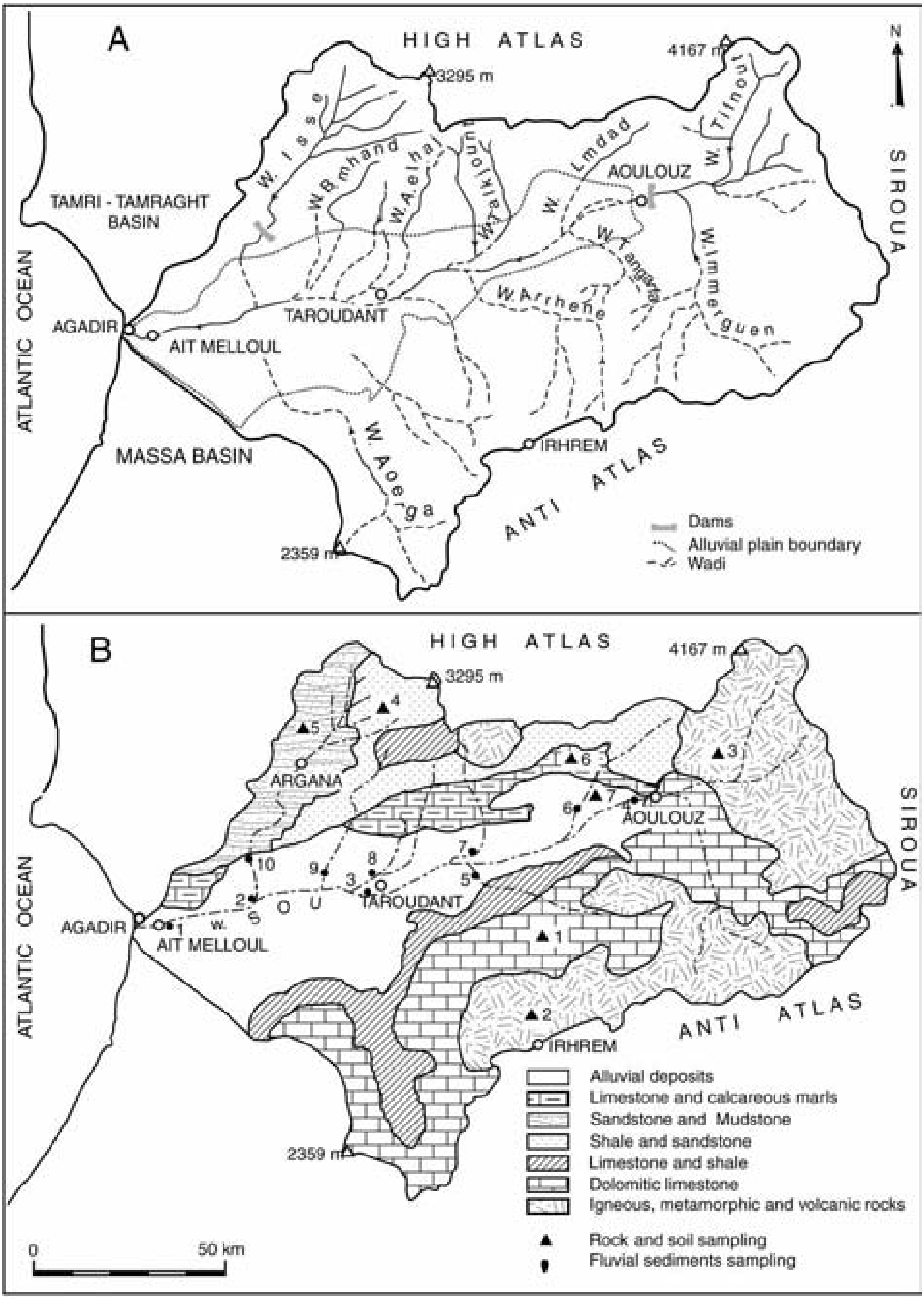

FIGURE 4 | **A) Hydrographic networks of Souss Wadi. B) Lithologic map and sample location.**

cific load has been estimated to range from 260 to 262 t/km^2/yr (Snoussi,1988; Lahlou, 2000).

The general framework of the Souss watershed shows some contrasts, opposing the three constitutive morphological and climatic zones of the basin: (i) the elevated mountain zone (High-Atlas and Siroua), that displays heterogeneous lithology and undergo semiarid to humid climate; (ii) the Anti-Atlas, only consisting of two major lithologic facies and submitted to semiarid to arid climate, (iii) the arid alluvial plain made up by deposits that are derived from the surrounding mountains. These contrasting morphoclimatic characteristics would have probably influenced the type and intensity of weathering and erosion exerted on the watershed, and on the quality and quantity of the detrital contributions fed into the Souss Wadi.

SAMPLING AND METHODOLOGY

In order to assess the effects of weathering on different lithologic facies in the diverse source areas, nineteen points were sampled considering three levels: the unaltered parent rock, the weathered rock and the surface layer or soil (Table 4). Seven widespread lithological formations were selected in the river basin. Several samples of fluvial materials were collected after flooding of the Souss wadi and its tributaries. They concerned the suspended matter in the downstream part (Ait-melloul) and the bank deposits which constitute a thin layer deposited after the floods in the rest of the hydrographic network (Fig. 4B).

The clay minerals were studied on a grain size fraction < 2 μm after being decarbonated (by HCl N/10) and washed several times with demineralised water. The separation of grain size fraction < 2 μm was carried out by settling and centrifugation. The obtained paste was spread out on three plates: the first was air dried, the second solvated with ethylene-glycol for 48 hours, and the third oven heated at 550°C for one hour. These three plates were analysed by X-ray diffraction in a Philips diffractometer (tube with a copper filament, nickel filter, adjusted to 35 kW and 25 mA). Finally, a computing data treatment was carried out in order to establish the qualitative curve (diffractogram), semi-quantitative estimation and I.D.S (Illite crystallinity index) of the clay association.

RESULTS AND DISCUSSION

Both source areas and alluvial deposits in the Souss River basin were analysed and the qualitative and semi-quantitative results of clay mineral analysis compared in order to establish their main characteristics, analogies and differences (Tables 4 and 5; Figs. 4B and 5A).

TABLE 3 | **Maximal discharges of flood rise (m^3/s) from 1963 to 1988.**

Date of flood	Aoulouz	Taroudant	Ait Melloul
07 - 02 - 1963	720	2698	1700
20 - 12 - 1963	180	956	1093
03 - 02 - 1965	615	331	1450
13/14-11-1967	1068	1915	2200
4/5- 01 - 1970	1264	502	1400
09 -02 - 1975	-	100	280
05 - 02 -1976	-	334	435
27/29-9-1976	735	430	262
28 - 01 - 1979	1365	1850	1650
16 - 11 - 1983	730	2228	1370
07 - 01 - 1985	378	1620	978
28 - 01 - 1986	88	420	770
25/26-10-1987	1650	1519	940
10 - 11 - 1988	516	840	1516
Average discharge	775.75	1054.26	1078.26

Based on data of the Hydraulic department of Agadir. See localities in Fig. 3.

The watershed clay mineral assemblage

The qualitative and semi-quantitative inventory of clay minerals in parent rocks, altered rocks and soils of the Souss basin shows a widespread predominance of minerals inherited from the parent rocks. Illite, chlorite and kaolinite reach up to 40% in the samples of friable limestone and marly limestone and up to 78% in the quaternary alluvial deposits on the plain. Nevertheless, transformed and/or neoformed minerals (smectite, vermiculite, palygorskite and mixed-layers of chlorite-vermiculite or chlorite-smectite) also occur, distributed according to the weathering conditions and the lithological composition of the source areas. Thus, palygorskite and neoformed smectite characterise the clay assemblages resulting from the weathering of the calcareous substrata in the lower altitude zones (Anti-Atlas tablelands and High-Atlas piedmonts) and of the carbonate encrusted quaternary alluvial deposits. Transformed smectite and chlorite-smectite mixed-layers occur in the Anti-Atlas relieves and the Siroua piedmonts. The occurrence of vermiculite and chlorite-vermiculite mixed-layers characterise the High-Atlas and Siroua summit areas. The observed vermiculite in the Siroua piedmonts is attributed to detrital lateral mixing, since the genesis of this mineral requires a wetter environment. Finally, smectite is widespread in the Argana corridor (Figs. 4B and 5A; Table 4).

TABLE 4 | **Composition of clay mineral assemblages in the source areas of Souss basin.**

Sampling Points-Type of sample	I	Ch	K	Sm	Ch-Sm	V	Ch-V	Pal
1s	30	44	0	15	0	0	0	11
1a	17	78	0	5	0	0	0	0
1r	100	0	0	0	0	0	0	0
2s	38	19	12	17	14	0	0	0
2a	44	56	0	0	0	0	0	0
2r	41	59	0	0	0	0	0	0
3s	42	9	13	11	8	17	0	0
3a	50	25	13	8	0	0	0	0
3r	49	45	0	6	0	0	0	0
4s	48	9	20	0	0	11	12	0
4a	81	10	0	0	0	0	9	0
4r	87	13	0	0	0	0	0	0
5s	68	5	4	23	0	0	0	0
5a	54	6	0	40	0	0	0	0
5r	100	0	0	0	0	0	0	0
6s	38	1	1	38	0	0	0	22
6a	55	12	10	23	0	0	0	0
7s	58	13	7	10	0	0	0	12
7a	45	21	20	14	0	0	0	0

Main lithological units
1: Palaeozoic dolomitic limestones; 2: Proterozoic igneous and metamorphic rocks of Anti-Atlas; 3: Proterozoic ignous and metamorphic rocks of Siroua and High-Atlas; 4: Mesozoic shales and sandstones of High Atlas; 5: Permo-triasic sandstones and mudstones of Argana corridor; 6: Cretaceous and Palaeogene limestones and marls; 7: Neogene and quaternary alluvial deposits.
Type of sample
r: unaltered parent rocks; a: altered rocks. s: soils.
Clay minerals
I: illite; Ch: chlorite; K: kaolinite; Sm: smectite; Ch-Sm: chlorite-smectite mixed layers; V: vermiculite; Ch-V: chlorite-vermiculite mixed layers; Pal: palygorskite.

See sample locations in Figs. 4B and 5A

This zonation of clay mineral assemblages in the source areas of the Souss Wadi basin accords well with their differing climatic, lithologic and topographic characteristics. Thus, in the more watered high altitude areas widespread, pervasive hydrolysis results in intense leaching of the alkaline cations (particularly potassium). This process unifies chlorite layers that consequently degrade first in chlorite- vermiculite mixed-layers and then in vermiculite (Table 4, samples 4r, 4[a] and 4s from the High Atlas; Paquet, 1969; Chamley, 1989; Parker and Rae, 1989; Duchaufour, 1991). In the middle altitude areas, alternation of wet and dry seasons leads to the transformation of chlorite into chlorite -smectite mixed-layers, then into smectite in a weathering environment which causes alkaline cation leaching and that is confining for silicium (Table 4, samples 2r, 2a and 2s from the Anti-Atlas; Tardy, 1969; Thorez, 1985; Snoussi, 1988; Velde, 1995). In the calcareous region, the decarbonitation linked to weathering is accompanied by neoformation of palygorskite and smectite resulting from the chemical concentration of elements by evaporation (Table 4, samples 6a and 6s from the piedmont of the High Atlas). The same process may occur in the low lying plain, where laterally supplied chemical elements are concentrated by evaporation and lead to the generation of calcareous crusts which are often associated with palygorskite and smectite neoformation (Table 4, samples 7a and 7s; Elmouden, 1992; Chamley, 2000).

The overall predominance of inherited clay minerals indicates a relatively mild weathering under the semiarid climate conditions that characterises the Souss Wadi basin region. Nevertheless, the minor transformed and neoformed clay minerals (smectite, vermiculite, chlorite-smectite and chlorite-vermiculite mixed-layers) can be used as tracers for fluvial sediments originating from various source areas.

Fluvial deposits and watershed relationship

Several previously developed studies have emphasised the good correspondence between the mineralogy of fluvial suspended particles and geological and pedological formations of the adjacent watershed (Weaver, 1989; Chamley, 2000). However the less resistant to transport minerals, particularly palygorskite (fibrous minerals) and mixed layers (badly crystallised) are usually destroyed during fluvial transport (Snoussi, 1988).

Several general observations can be established on the basis of the clay mineral assemblages recorded in fine-grained fluvial sediments of the Souss Wadi and its main tributaries (Fig. 5B and Table 5). The clay mineral assemblages recorded in the sediments of different tributaries (Fig. 4B) accords well with the clay mineral assemblages recognised in their source areas, with predominance of inherited minerals (illite: 25 to 74%, chlorite:10 to 28% and kaolinite: 4 to 19%) and transformed smectite (6 to 22%). The other neoformed clay minerals occur according to the neighbouring source areas. In Aoulouz gorges, which collect high Souss waters (Siroua and the east part of the High-Atlas), the clay mineral assemblage is characterised by the occurrence of palygorskite (14%) that originated from the calcareous rocks cropping out at the piedmont zones. Chlorite-vermiculite mixed-layers (9%) coming from Siroua high altitude areas also occur. In the Arrhene tributary, which drains the Anti-Atlas, the clay mineral assemblage includes palygorskite (5%) and smectite (9%) with a total absence of chlorite-smectite mixed-

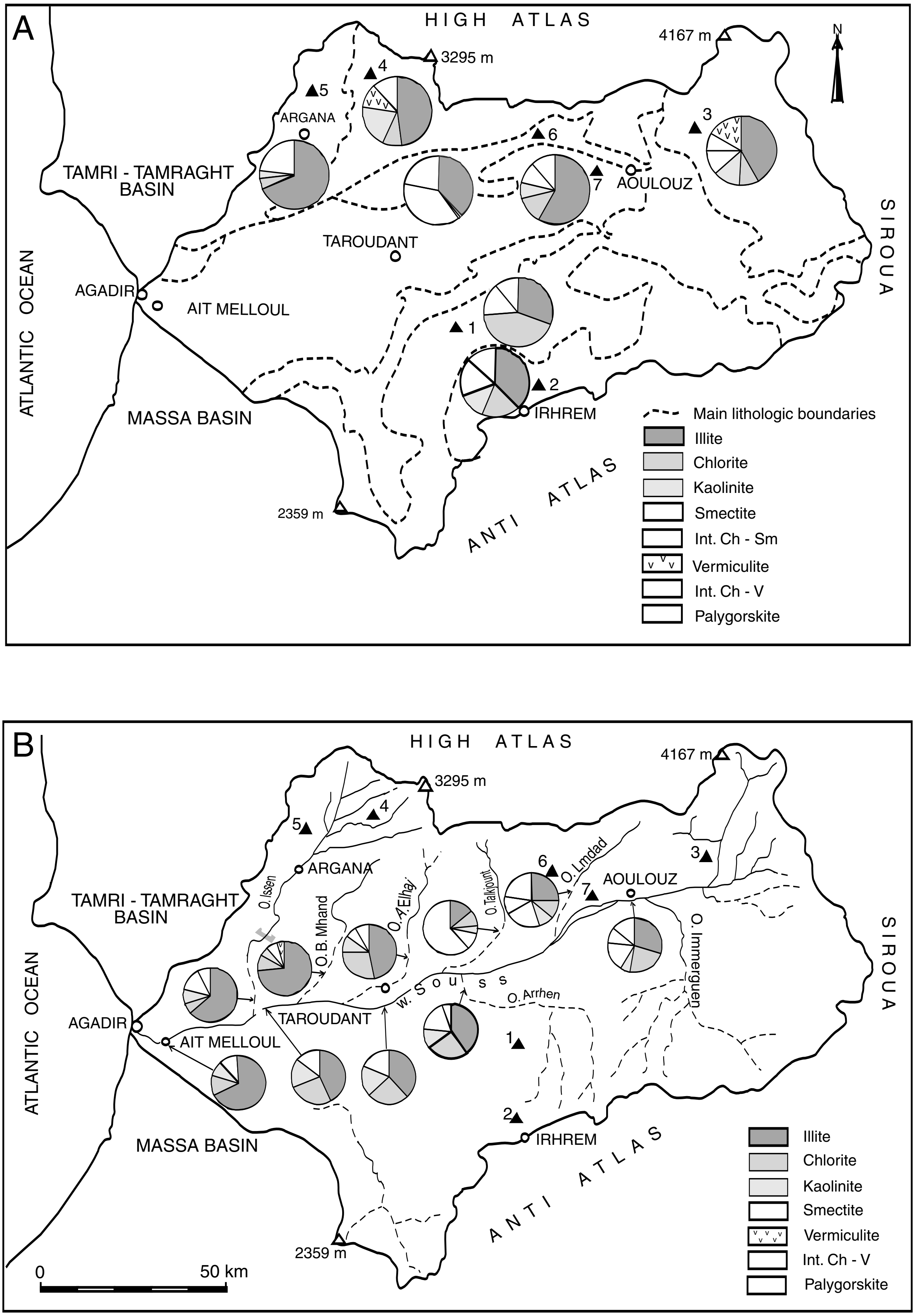

FIGURE 5 | **A) Clay mineral assemblages recorded in the soils developed on the main lithologic formations of the Souss watershed. B) Clay mineral assemblages in fluvial sediments of Souss Wadi and its tributaries.**

TABLE 5 | **Clay mineral assemblages in fluvial sediments of Souss wadi and its tributaries.**

Sampling points	I	Ch	K	Sm	Ch-Sm	V	Ch-V	Pal
1	67	13	9	11	0	0	0	0
2	42	29	17	13	0	0	0	0
3	38	25	19	18	0	0	0	0
4	30	23	6	18	0	0	9	14
5	40	25	11	19	0	0	0	5
6	25	12	8	22	0	0	10	23
7	14	10	4	10	0	0	0	62
8	47	28	10	6	0	0	0	9
9	74	9	5	7	0	5	0	0
10	64	6	8	14	0	0	0	8

Sampling points
1 to 4: Fluvial sediments from Souss wadi;
5: Fluvial sediments from Anti-Atlas tributary;
6 to 10: Fluvial sediments of High-Atlas tributaries.
Clay Minerals
See Table 4
See sample locations in Figs. 4B and 5B

layers generated at high altitude; this shows that the Anti-Atlas detrital contribution is low, a fact that accords well to the hydroclimatic data. In Lmdad tributary, which drains the High-Atlas summits (2500 to 4167 m of altitude), the clay assemblages contain chlorite-vermiculite mixed-layers (10%) and a large proportion of smectite and palygorskite (18 and 14% respectively). This shows the large contribution from the calcareous piedmonts areas. The Talkjount tributary presents a clay mineral assemblage dominated by palygorskite (62%), indicating that most of this sediments are fed from the very friable marl calcareous outcrops in the watershed. The Ait Elhadj, Beni Mhand and Issen tributaries, which drain Palaeozoic and Triassic age shale, silty, and sandstone formations display a clay mineral assemblage dominated by inherited clays, especially illite (47 to 70%). This would account for the large contribution of the shale-dominated formations to the solid load of these tributaries.

The alluvial sediments from Souss downstream (Ait Melloul and Ouled Taima stations) are dominated by inherited minerals (42 to 67% of illite and 13 to 29% of chlorite). These sediments yielded a low proportion of smectite (11 to 13%) and show no palygorskite that, on the contrary, is well represented in the low-lying plain zones. This clay mineral assemblage resembles that of Ait Elhadj, Beni Mhand and Issen tributaries and indicates their major contribution to the solid load delivered to the ocean. The absence of palygorskite in the downstream part is explained by the large vulnerability of this fibrous mineral destroyed during the fluvial transport (Snoussi et al., 1990).

TABLE 6 | **Variation of Dunoyer de Segonzac index (I.D.S) in the Souss Wadi Basin. A: Parent rocks and soils. B: Fluvial sediments.**

A

Sampling points	1	2	3	4	5	6	7
Soils	0.3	0.4	0.4	0.3	0.4	0.3	0.4
Rocks	0.2	0.2	0.2	0.2	0.2	0.2	0.4

B

Sampling points	1	2	3	4	5	6	7	8	9	10
	0.2	0.2	0.3	0.2	0.4	0.3	-	0.4	0.2	0.3

From this comparison it is proposed that the clay minerals in the fine grained sediments of all Souss tributaries reflect major contribution from calcareous and marly calcareous formations from the piedmont as well as from shale and silty formations that crop out in the high altitude zones (High Atlas). The solid materials fed into the Atlantic ocean are dominated by these contributions.

According to Dunoyer de Segonzac (1969), the comparison of illite crystallinity index (I.D.S) in fluvial deposits, soils and parent rocks shows a good illite crystallinity in the wadis draining the High-Atlas and in the Souss downstream deposits. This fact reflects a contribution to alluvial sediments derives not only from surface weathering layers and soils, but also directly from the parent rock, as well as the importance of denudation, accentuated by the abrupt relief, in some of the high altitude zones (Table 6A and 6B).

CONCLUDING REMARKS

Illite, chlorite and kaolinite, derived directly from the substratum weathering, dominate the clay assemblages recorded in altered rocks and soils of the semiarid Souss Wadi watershed. Nevertheless, the transformation and neoformation of diverse clay minerals, mainly controlled by changing climatic, lithological and topographic conditions, enables one to establish three distinctive kinds of source areas: High altitude, largely watered source areas where chlorite is transformed into vermiculite; middle altitude, drier areas where more pronounced seasonal contrast induces the transformation of chlorite into chlorite-smectite mixed layer, and, finally, low altitude carbonate-dominated rock zones, with gentle slopes, where evaporation and chemical concentration result in smectite and palygorskite neoformation.

In river basins such as the Souss Wadi basin the original clay mineral assemblages may include the abovementioned neoformation clay minerals that are useful as environmental indicators and as local to zonal signatures of sediment contribution. Nevertheless, confirming previous studies, the original clay assemblages tend to be homogenised as a consequence of destruction of the less resistant clay minerals during fluvial transport. Thus, inherited illite, chlorite and kaolinite, derived directly from the substratum, dominate the clay assemblages in the alluvial sediments deposited in the downstream parts of the main fluvial collectors, far away from the local source areas.

The comparison between the clay mineral assemblages recorded in the alluvial deposits of the different tributaries of the Souss Wadi and their source areas reflects the preferential contribution of each area to alluvial sediments. Thus, the friable and marly calcareous formations, which crop out at the piedmonts, the shale, silty and sandstone-dominated formations of the High-Atlas and the older river bank deposits are the main sediment contributors to the wadi system. The High-Atlas lithology and relief, with steeper slopes, favour an intense denudation and erosion. Consequently wadi deposits fed from the northern river basin areas dominate the materials delivered to the ocean. The wide tabular topography and the calcareous-dominated lithology in the Anti-Atlas (with largely karstified units that facilitates the water infiltration) preclude significant sediment contribution.

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